CRANFIELD UNIVERSITY

WANG XIAOYANG

Aircraft Fuel System Prognostics and Health Management

School of Engineering
MSc by Research

MSc Thesis
Academic Year: 2011 - 2012

Supervisor: Dr. Craig Lawson
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ABSTRACT

This thesis contains the specific description of Group Design Project (GDP) and Individual Research Project (IRP) that are undertaken by the author and form part of the degree of Master of Science.

The target of GDP is to develop a novel and unique commercial flying wing aircraft titled FW-11. FW-11 is a three-year collaborative civil aircraft project between Aviation Industry Corporation of China (AVIC) and Cranfield University. According to the market analysis result conducted by the author, 250 seats capacity and 7500 nautical miles were chosen as the design targets.

The IRP is the further study of GDP, which is to enhance the competitive capability by deploying prognostics and health management (PHM) technology to the fuel system of FW-11. As a novel and brand-new technology, PHM enables the real-time transformation of system status data into alert and maintenance information during all ground or flight operating phases to improve the aircraft reliability and operating costs. Aircraft fuel system has a great impact on flight safety. Therefore, the development of fuel system PHM concept is necessary.

This thesis began with an investigation of PHM, then a safety and reliability analysis of fuel system was conducted by using FHA, FMEA and FTA. According to these analyses, fuel temperature diagnosis and prognosis were chosen as a case study to improve the reliability and safety of FW-11. The PHM architecture of fuel temperature had been established. A fuel temperature prediction model was also introduced in this thesis.

Keywords:

PHM, Reliability, Safety, Fuel temperature prediction, Flying wing

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LIST OF ABBREVIATIONS

AC	Alternating Current
ACMF	Aircraft Conditioning Monitoring Function
AVIC	Aviation Industry Corporation of China
APU	Auxiliary Power Unit
BIT	Built-in Test
c_p	Specific Heat Capacity
C	Specific Fuel Consumption
CG	Centre of Gravity
CMC	Central Maintenance Computer
CU	Cranfield University
CAAC	Civil Aviation Administration of China
COMAC	Commercial Aircraft Corporation of China
DC	Direct Current
DoD	Department of Defence
dU	Internal Energy
EASA	European Aviation Safety Agency
ECS	Environmental Control System
EICAS	Engine Indication and Crew Alerting System
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
FFP	Fuel Freezing Point
FHA	Functional Hazard Analysis
FRS	Flammability Reduction System
FMC	Fuel Management Computer
FMEA	Failure Mode and Effects Analysis
FMECA	Failure Modes, Effects and Criticality Analysis
FTA	Fault Tree Analysis
GDP	Group Design Project
GDP	Gross Domestic Product
ICAO	International Civil Aviation Organization
IRP	Individual Research Project
IRP	Integrated Refuel Panel

M	Mach number
$\dot{m}_{inlet}$	Fuel Flow Rate Enter the Fuel Tank
$\dot{m}_{outlet}$	Fuel Flow Rate Leave the Fuel Tank
NASA	National Aeronautics and Space Administration
NTSB	National Transportation Safety Board
OBIGGS	On-Board Inert Gas Generating System
PHM	Prognostics and Health Management
PPP	Purchasing Power Parity
T_{inlet}	The Temperature of Fuel Enter the Fuel Tank
T_{outlet}	The Temperature of Fuel Leave the Fuel Tank

1 Introduction

1.1 Background of PHM

Due to the violent competition among civil airlines, it is increasingly eager that the demand for high efficiency civil aircraft. The appearance of Prognostics and Health Management (PHM) system, as a novel and brand-new technology, brings considerable benefits to such a need.

1.1.1 PHM Definition

According to Kalgren, PHM is “a health management approach that utilizes measurements, models, and software to perform incipient fault detection, condition assessment, and failure progression prediction” [1]. Health management concept is the capability to make appropriate decisions about maintenance actions based on real-time monitoring, diagnosis and prognosis information, available resources, and operational demand [2]. The PHM works through a network of onboard sensors collecting status data of the aircraft’s components, subsystems and system level elements, then transforms the data into information by using the built-in software and models, and then transfers them to the associate crews. The PHM system enables the real-time transformation of system status data into alert and maintenance information during all ground or flight operating phases, which can support pilots and ground maintenance crews for decision making.

1.1.2 PHM Functions

The primary PHM functions include real-time detection/monitoring, diagnosis and prognosis of aircraft health status. These primary functions are discussed in this thesis. The PHM also has other functions such as Mitigation and Integrity Assurance.

The goal of the detection element is to develop validated technologies to detect anomalies from adverse events throughout the aircraft in hardware and in software, and the interactions between these two classes of systems [3]. Based on the advanced sensors technologies, the real-time detection/monitoring can track and acquire the foundational data of ongoing aircraft health status systemically.

The goal of the diagnosis element is to develop integrated and validated technologies to determine the causal factors, the nature and severity of an adverse event and to distinguish that event within a family of potential adverse events [3]. The health state data acquired by the detection function can be transmitted to the diagnosis function to isolate and classify the possible anomalous events rapidly. It means that, based on the detection function, diagnosis can identify the failure source or isolate the fault to related Line-replaceable unit (LRU).

The goal of the prognosis element is to determine, given the information from the detection and diagnosis health management systems and other systems, a validated estimate (i.e., with a measure of confidence) of the remaining useful life of the candidate failures generated by the diagnosis element [3]. Based on the aircraft health status data and advanced built-in models, the prognosis function can predict the remaining useful life (RUL) of relative system or LRU, or even forecast the remaining occurrence time of anomalous events which may cause catastrophic disaster. In other words, the prognosis enables the operators to forecast most of the relevant failures condition before it happens.

1.2 PHM Benefits

The PHM has the following advantages:

1. Reduced cost and increased revenue.
2. Improved aircraft safety and reliability.
3. Minimised maintenance actions.
4. Improved mission readiness and availability.
5. Increased dispatch rate and competitiveness.
6. Allow operators to assess the effectiveness of their fleets.

1.3 PHM Architecture

Generally, the architecture of PHM system comprises a decision unit and some subunits to process different aircraft parameters. The architecture of a typical PHM system is shown as Figure 1-1.

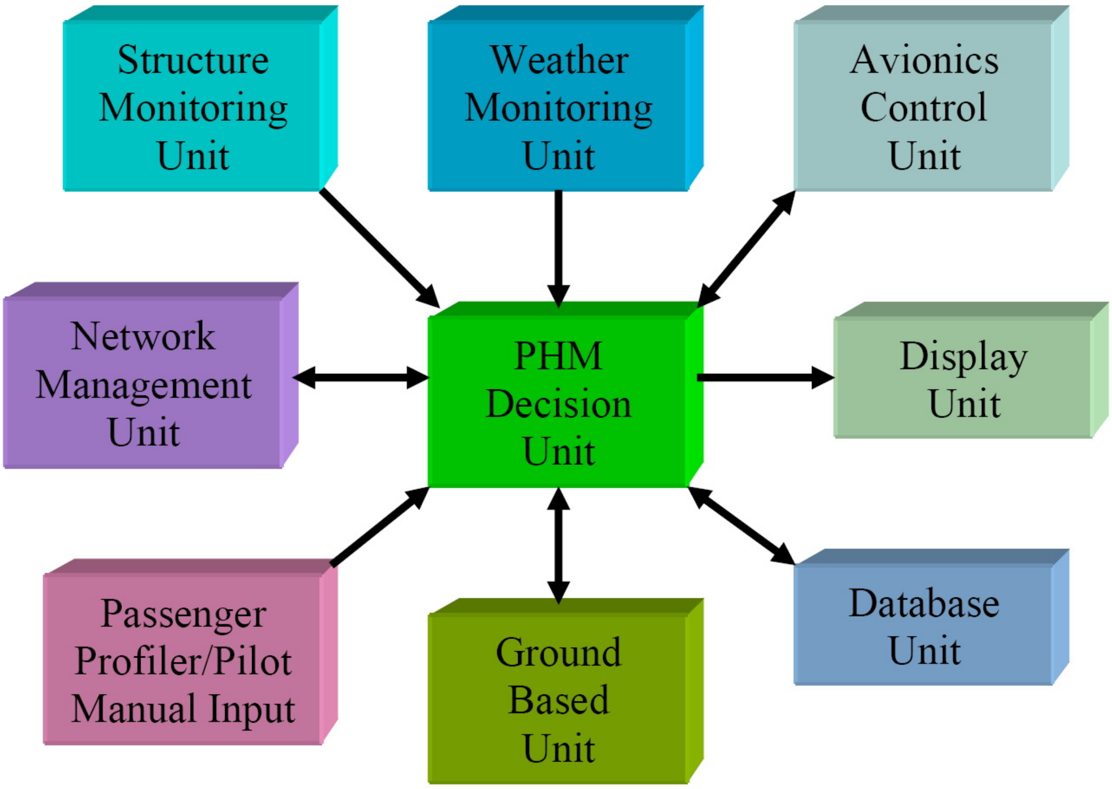


Figure 1-1 A Typical PHM Architecture [4]

1.4 Aircraft Fuel System and PHM

The primary function of the fuel system is to store enough fuel required by the mission and supply fuel to the engine and APU (auxiliary power unit) at proper rate, pressure and temperature under any operating conditions safely and continuously. During the mission, the fuel system should maintain the Centre of Gravity (CG) of aircraft within designated range. The fuel in the fuel tank also can be used as heat sinks to cool down other systems or components.

Aircraft fuel system has a great impact on flight safety since most of accidents associated with fuel system lead to hazardous and even catastrophic events. The aircraft cannot sustain flight without the pressurised fuel flow to the engine since the aircraft thrust and power is provided by engine. The deployment of the PHM into the fuel system can improve not only the aircraft safety and reliability, but also the turn-around time so as to increase the dispatch rate and competitiveness.

1.5 Problem Statement

As discussed in the previous paragraph, introducing PHM technology into the fuel system is very important since it has lots of benefits to the overall aircraft performance. However, as a new technology, little practical application to the fuel system has been done. Thus, a long period of time is needed for the PHM technology of fuel system development.

The aircraft fuel system employs lots of components or LRUs, thus the real-time monitoring/detection, diagnosis and prognosis functions rely on the advanced hardware and software to handle the complicated parameters. This thesis will focus on the onboard software, especially the built-in prognostic model. It is a great challenge to find a proper software improvement way to improve the current fuel system PHM technology.

1.6 Research Objectives

This research aims to develop a fuel system health management method and implement this new technology to the fuel system of Flying Wing aircraft (FW-11) which is the Group Design Project (GDP) the author participated.

FW-11 is a three-year collaborative civil aircraft project between Aviation Industry Corporation of China (AVIC) and Cranfield University. It is an innovative 250-seat flying wing aircraft whose design range is 7500 nautical miles. The detail information and the work accomplished by the author are shown in the Appendix A.

This Individual Research Project (IRP) is the further study of GDP. The temperature of fuel is chosen as a case study since this parameter has great impacts to the flight safety.

The objectives of this research project are:

1. To design an assumed fuel system architecture of the FW-11.
2. To develop a PHM method and implement it in the fuel system of FW-11. By deploying this method, it can greatly increase the competitive capability of FW-11.
3. To develop an onboard fuel tank temperature PHM architecture. In order to deploy this technology into the practical application of aircraft fuel system, a fuel temperature prediction model is needed to be developed.

1.7 Research Scope and Assumption

The aircraft fuel system becomes more complicated with the development of technologies. It consists of numerous electrical, electronic and mechanical components such as pumps, valves, tubes, and sensors to perform the various operating functions. Thus, in order to accomplish the research targets, this research will base on the fuel system of FW-11. It means that the assumed fuel system architecture of FW-11 should be accomplished firstly. All the IRP research work will be based on this assumption.

Furthermore, shown as Table 1-1, the PHM technology is a wide concept which covers various aspects and fields associated with flight safety. So this thesis will focus on developing and implementing the main PHM functions illustrated in the previous section.

Table 1-1 PHM Technology [2]

Aircraft Systems Diagnostics, Prognostics and Health Management Systems Requirements Map (*Based on DPHM Workshop, Ottawa, 18 November 2004)		
*Aeropropulsion	Structures/ Airframe	Systems Interation/ Health Management
Data Collection and Communication	Crack detection Monitoring	Need DPHM to control/predict cost
Diagnostics	Environmental monitoring (corrosion, Temp, Load)	Requires integration - Full and smart integration - Easy access to data, central data source
Fault Detection	Strain monitoring	Availability/reliability (push back cost)
Fault Isolation	Vibration	Planned environment (no surprises!)
Prognostics	Accessibility/embedded sensors	Paperless/Electronic Signature (no manual data entry)
Failure Mode, Effects and Criticality Analysis (FMECA)	Pressures/G-forces (acceleration)	Certification process for new technology
Component Life Tracking	External noise – ground fire	Integration of standards
Life Remaining Analysis	GAG cycle	Emissions mitigation
Performance Trending	Torque variations	Obsolescence Avoidance
Fault Prediction	Certification	Feedback Loop
Health Management	Flight hours	Need to take into account user inputs as early as possible - Commercial - Military - Other
Fault Assessment	In-flight and on-board information/data integration - Maintenance history - Intelligent management of data	
Fault Reporting	Materials/design data - Fault progression model	
Supply Chain Integration	Active excitation for fault detection/isolation	
Fault Accommodation	Sensitivity to anomaly detection – flight duration	
	Knowledge of residual stresses	
	Lifing models	

1.8 Methodology

As a new technology, few airliners in the world have deployed the practical fuel system PHM successfully. Thus, the public articles about the aircraft fuel system PHM are inadequate. New methods are expected to be appeared and verified to develop this new technology.

In the PHM research procedure, the first step is to find out the critical system functions need to be monitored or detected by using approved method. Consequently, the system malfunctions or component failures need to be identified through an appropriate diagnostic approach, and then a reasonable prognostic method should be confirmed to predict the RUL of subsystems/components or forecast the remaining occurrence time of anomalous events which may cause catastrophic disaster. The real-time detection/monitoring, diagnosis and prognosis data should be recorded in the onboard database or transmitted to the warehouse via the data link between ground and aircraft.

Finally, the fuel temperature prognostic method in the fuel tank will be discussed as a case study.

1.8.1 Detection/Monitoring

The fuel system consists of so many components to perform the various functions that the identification of the signal or LRU status need to be detected or monitored for the following analysis and process is necessary. It seems unreasonable to monitor all the signals and components status during flight or on the ground whilst considering the increase of complexity and weight. Thus, the system critical functions must be identified for the detection/monitoring function.

In order to build a reliable PHM system, the following mature methods are employed to identify the system and component failure modes:

1. Functional Hazard Analysis (FHA)
2. Failure Mode and Effects Analysis (FMEA)
3. Fault Tree Analysis (FTA)

The critical system functions can be investigated by using these analysis methods above.

1.8.2 Diagnosis

Diagnosis is the specific process of recognising the status of a subsystem or a component to perform its functions based on the results of detection/monitoring function. Generally, diagnostic capability is often considered a two step process, the first being the identification that a fault has occurred and then localizing the cause of the fault to a specific component, ideally at the lowest assembly level to reduce costs [2].

The following diagnostic systems have been applied on aircraft:

1. Rule-based experts system.
2. Model-based reasoning system.
3. Case-based reasoning system.
4. Learning system.

This thesis focuses on the rule-based expert system and model-based reasoning system. The detail discussion of these diagnostic systems is in the literature review. In order to fulfil the research aims, the FTA is used to develop an intelligent rule-based expert system and a fuel temperature prediction model is also constructed for the mode-based reasoning system.

1.8.3 Prognosis

Prognosis is the special course of predicting the RUL of a crucial component based on the detection/monitoring and diagnosis. It can also forecast the crucial parameters during flight. Five mainly used prognostic approaches are shown below:

1. Statistical reliability and usage-based approach
2. Trend-based evolutionary approach
3. Data-driven model-based approach
4. State estimator based approach
5. Physics-based modelling approach

In this thesis, a data-driven model-based approach is used to predict the fuel temperature trends during flight. The detail discussion of these prognostic approaches is in the literature review.

1.8.4 Fuel Temperature Prediction

The fuel temperature has great impact on the flight safety. Cold fuel will cause the fuel-feed line blockage and hot fuel will increase the risks of fuel tank explosion. For the international civil airliners, the fuel capacity is enormous.

Once the fuel temperature beyond the danger point, it needs a long time to recover this parameter after specific actions have been done.

For a fixed aircraft fuel system, the rate at which the fuel temperature changes is a function of air temperature, heat from heat exchangers, specific heat capacity, the inlet fuel flow rate, the outlet fuel flow rate, the inlet fuel temperature, the fuel mass within the fuel tank, the fuel temperature in the fuel tank and time. Based on the thermodynamic study of the fuel tank heat transfer mechanism, a formula of fuel temperature changes can be derived. The prognostic method is based on this formula which will be discussed later.

1.9 Thesis Organization

There are seven chapters in this thesis. The second chapter is the literature review of the PHM technology. Chapter three introduces the assumed fuel system architecture of FW-11, followed by Chapter four which is the fuel system study including FHA, FMEA and FTA. After these analyses, fuel temperature is selected as the case study to be discussed in Chapter five. Chapter six is the fuel temperature PHM study. The fuel temperature PHM architecture which integrates the monitoring, diagnosis and prognosis functions is established. The diagnostic function is achieved by using rule-based expert system and model-based reasoning system. The data-driven model-based prognostic approach is used to achieve the prognostic function. The last chapter is the conclusion and future work of IRP.

2 Literature Review

2.1 PHM Technology Overview

2.1.1 PHM Outline

The definition of PHM concept is “the processes, techniques, and technologies used to design, analyse, build, verify, and operate a system to prevent faults and/or mitigate their effects” [5]. PHM develops and combines lots of concepts, technologies and management methods. Table 2-1 shows the evolution of health management technology of Department of Defence (DoD) and NASA.

Table 2-1 Evolution of Health Management Technologies [5]

	DoD	NASA
1950s	• Reliability analysis • System Test and Evaluation • Quality Methods	• Reliability Analysis • System Test and Evaluation
1960s	• Modelling • Failure Analysis	• Modelling and Simulation • Failure Analysis • Telemetry of Data • Systems Engineering
1970s	• System monitoring • Reliability Centred Maintenance • Systems Engineering • Built In Test (BIT)	• System Monitoring • On-board fault protection • Redundancy management • Byzantine fault theory
1980s	• Expanded BIT • Data buses and digital processing • Engine Health Monitoring • Total Quality Management	• Expanded BIT • Data buses and digital processing
1990s	• Integrated Diagnostics • Flight Data Recording	• Diagnostics • Vehicle Health Monitoring • Vehicle Health Management • System Health Management
2000s	• Prognostics • Integrated Vehicle Health Monitoring • Integrated Vehicle Health Management	• Integrated System Health Management • Integrated System Health Engineering and Management

It is clear that the derivation of current health management technologies is aviation flight safety concepts and techniques. The practical application of PHM technology, such as diagnostics, condition-based maintenance, prognostics, and health management, was from 1970s. A-7, for which the Engine Monitoring

System was developed, is the milestone of the early PHM technology, shown as Figure 2-1.

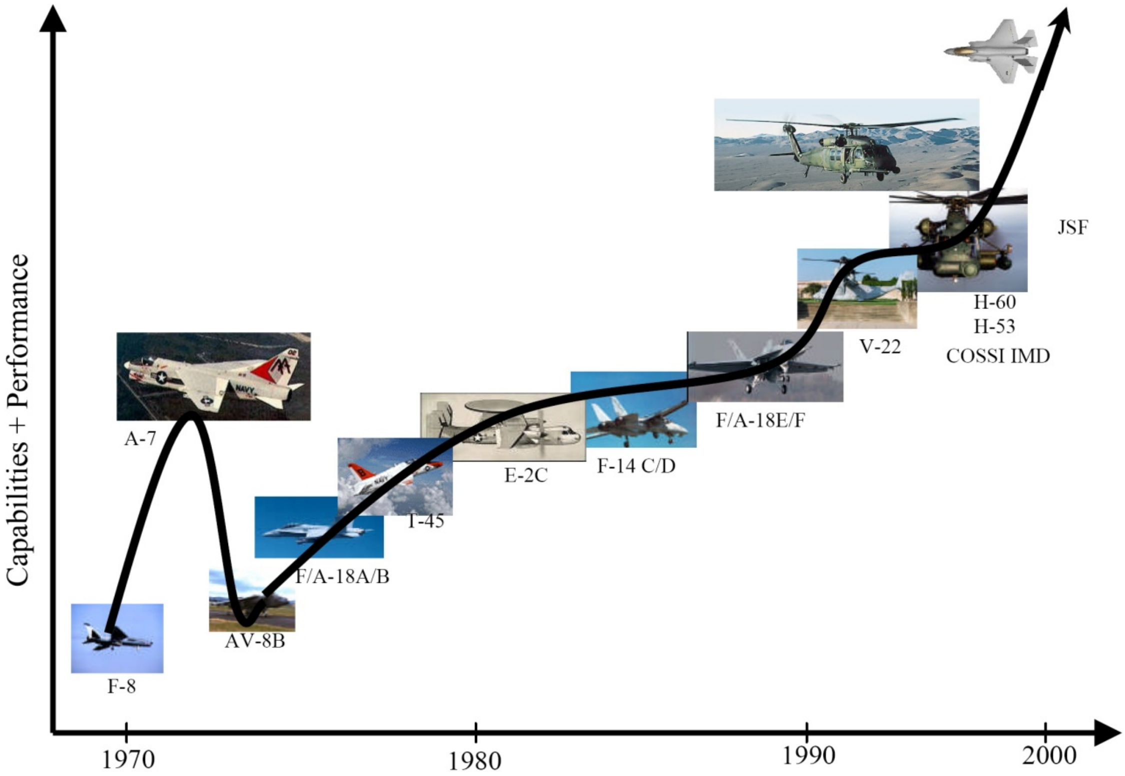


Figure 2-1 Relative Evolution of PHM Systems for Navy Aircraft [6]

2.1.2 PHM Technical Approach

Because of the complexity of PHM technology, it is divided into four levels generally. Figure 2-2 shows the overall technical approach of PHM technology.

Level 1 is the foundational research to support the whole project. Level 2 provides the validated technologies of the primary aircraft systems to enable the Level 3 whose goal is to develop integrated tools enabling the PHM functions. The target of Level 4 is to develop validated multidisciplinary PHM technologies, tools and techniques to enable the PHM functions. The research results of each level are finally integrated to realize the PHM technology into practical application.

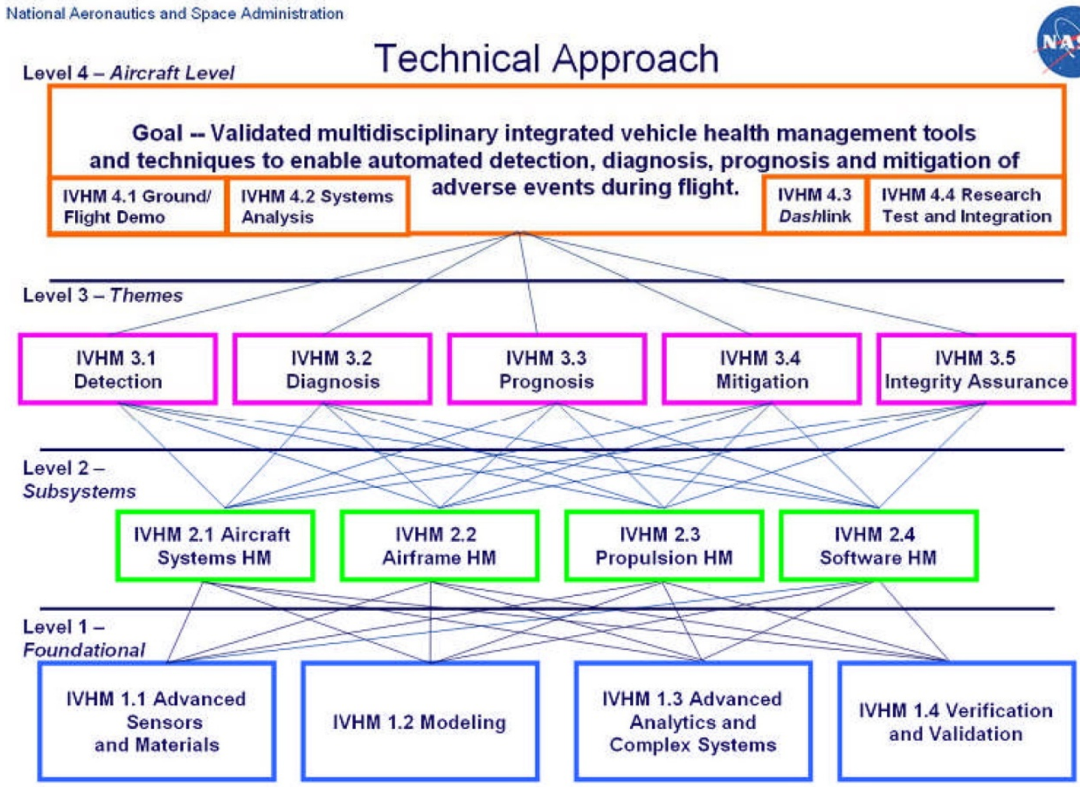


Figure 2-2 PHM Technical Approach [3]

2.1.3 Current State of the Art

The current PHM system focuses on putting various onboard sensors and intelligent software to interpret the output streams automatically. These data were provided to prognostic systems as inputs to assess the structural integrity and remaining component/subsystem life. One of the state-of-the-art health management systems is Honeywell's Aircraft Diagnostic and Maintenance System (ADMS) [3].

The ADMS is an avionics system in which fault propagation model is used in the Boeing 777. It is evolved from several previously used maintenance system. The ADMS includes the Central Maintenance Computer (CMC), Aircraft Conditioning Monitoring Function (ACMF), and the built-in-test (BIT) functionality of the various systems on the aircraft. It covers more than 200 aircraft subsystems and provides maintenance interface to all subsystems.

ADMS performs root cause diagnostics to eliminate cascading faults and provide correlation between system faults and flight deck effects [3].

2.2 PHM Functions

The figure below shows a typical architecture of health management operating functions. It is a reflection of the time-dependent repetitive feedback processes typical of dynamic systems [5]. This figure illustrates the typical PHM technologies and its operating process of status monitoring, failure detection, data transmission and response, diagnostics, prognostics, and maintenance. The relation between the primary functions of PHM technologies also is shown in this chart.

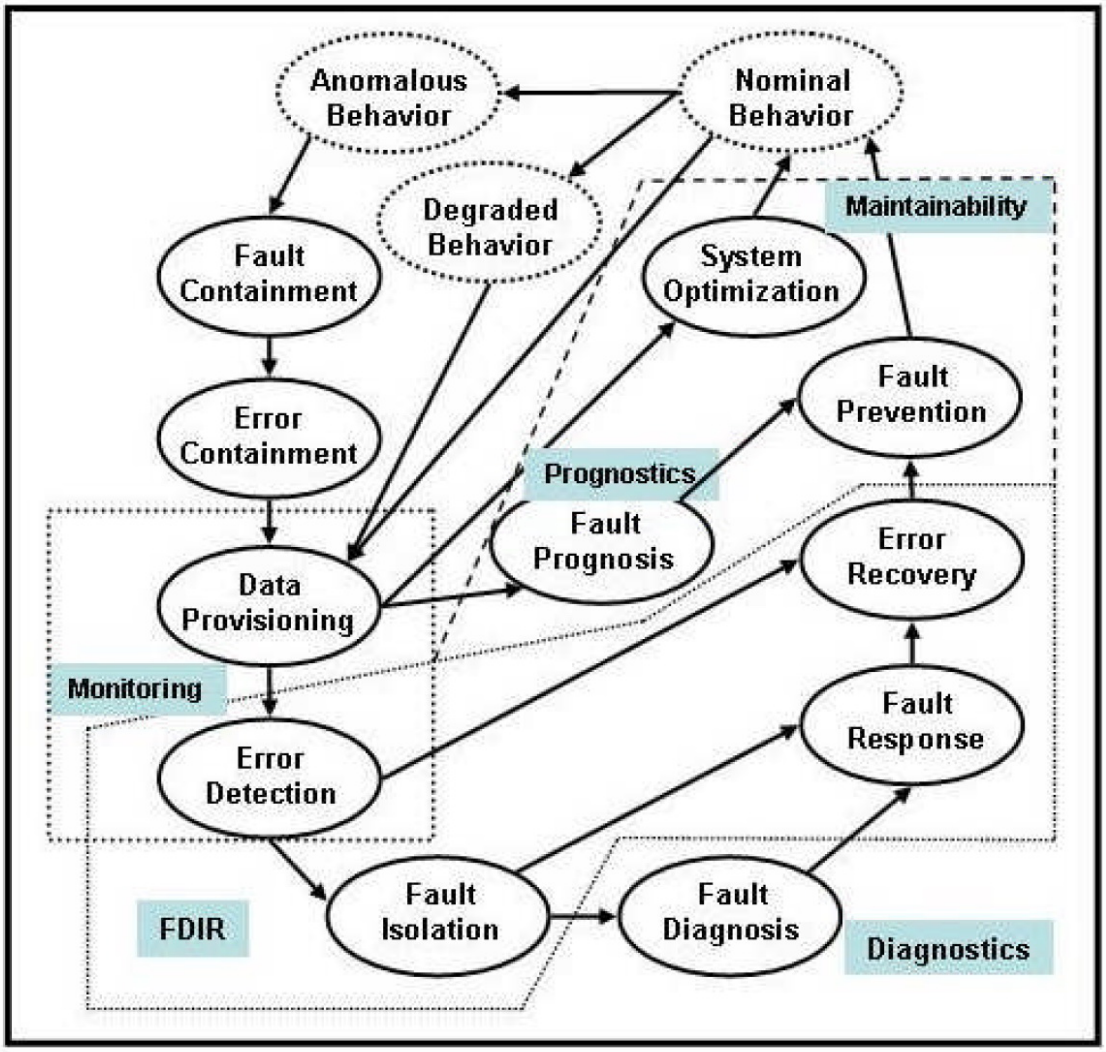


Figure 2-3 Health Management Functional Flow Chart [5]

According to the flow chart above, the following process are required while determining a system health status:

1. Detecting the symptoms of failure, from collection of raw sensor data to analysis and tests;
2. Diagnosis of the root cause;
3. Determining the effects of the condition;
4. Predicting the progression of the conditions [7].

2.3 PHM Technologies

2.3.1 Monitoring

Currently, the monitoring function capabilities in PHM mainly comprise the sensor technology, data acquisition/extraction and data communication. It means that the current development of monitoring function is focusing on the performance of data acquisition and bus transmission. All these issues are not included in this IRP report. The author is trying to determine the parameters or component status which needed to be acquired to fulfil the fuel system monitoring function.

In order to get the key parameters which have great impacts to the aircraft flight safety, the FHA and FMEA approaches are used to analyse the fuel system. Both FHA and FMEA are fundamental research approaches not only for implementing the monitoring function, but also for the diagnostic and prognostic capability.

2.3.2 Diagnosis

As an essential function of PHM technology, diagnosis is the procedure of detecting and identifying the cause of any adverse or abnormal events. This capability is based on sufficient data from monitoring system. The results of FHA and FMECA are also required to define the function and failure modes of each component or subsystem. Currently, diagnostics employ system FHA, FMECA, FTA results and combine with detected data to identify the causes and severity of an adverse event. As for the diagnostic system, rule-based expert system, case-based reasoning system, model-based reasoning system, and learning system are commonly used to diagnose anomalous conditions based on the signals from the detection/monitoring system [8].

The typical diagnostic procedure consists of three steps: observation, comparison and diagnosis which are shown as figure below.

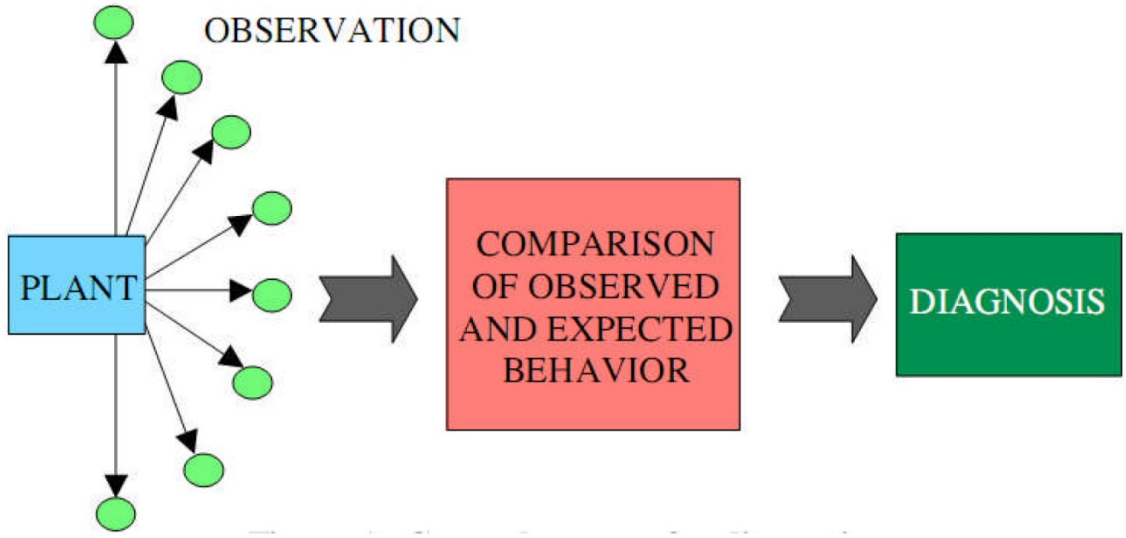


Figure 2-4 Typical Diagnostic Procedure [8]

Normally, observation is based upon the detection/monitoring techniques to obtain the essential data or signals such as voltage, current and temperature. In the second step, the primary functions of the comparison are data or signals processing which include comparing the observed data with expected behaviour and determining the status of key components or parameters. Lastly, the diagnostic reasoning engine is used to identify and localise the cause of adverse event to a specific component or casual factor. There are four widely used diagnostic techniques which are shown in the following parts.

2.3.2.1 Rule-based Expert System

As a typical artificial intelligent technique, rule-based expert system has widely application for diagnostic tasks where expertise and experience are available but deep understanding of the physical properties of the system is either unavailable or too costly to obtain [8].

The basic reasoning rule statement is “if-then-else”. These “rules” are simple patterns and the reasoning engine will search for the matched patterns in the data [2]. A set of rules can be incorporated into a rule-based expert system, which can then be used to generate diagnostic solutions [8].

The rule-based reasoning chaining is illustrated below. The first step is to match the observed facts and established rules. If these two items can totally match through only one rule, the diagnostic result will be implemented directly. If more than one rule matched, a pre-defined strategy is used to establish and examine the conflict set. The priorities of applicable rules were assigned by this strategy [8].

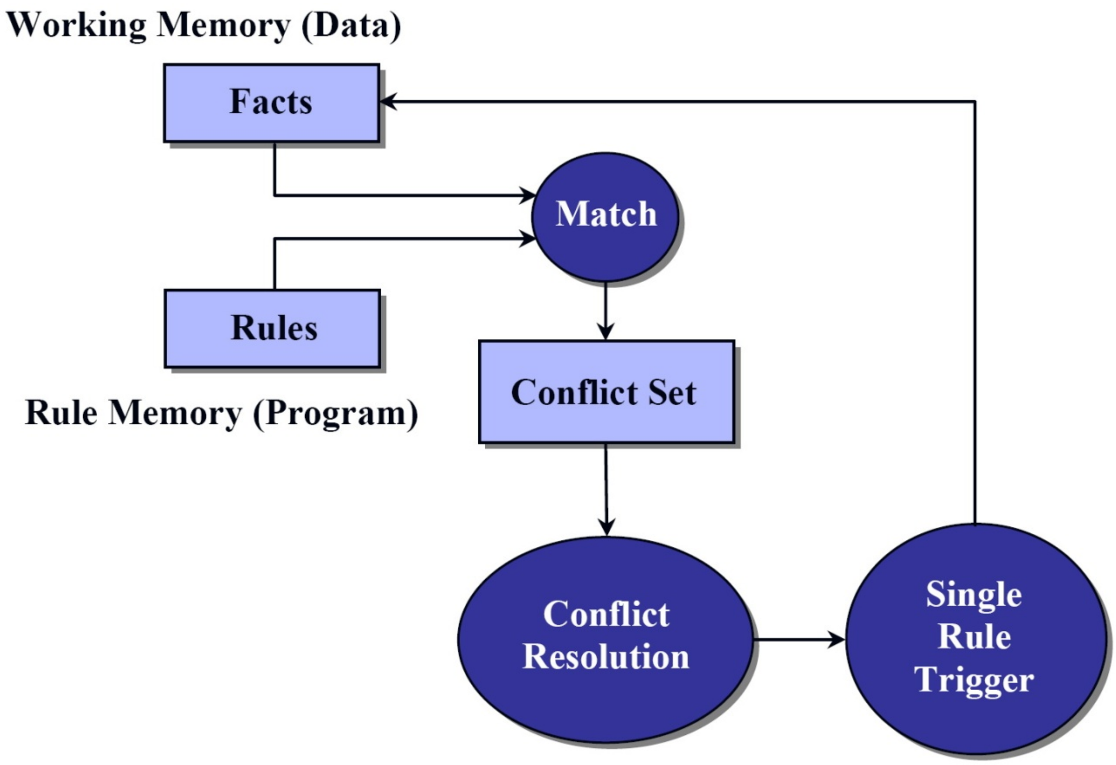


Figure 2-5 Rule-based Expert System [8]

2.3.2.2 Case-based reasoning system

Case-based reasoning system is a specific reasoning engine of knowledge solutions which uses past problems to solve new problems. It refers to both a cognitive and a computational model of reasoning by analogy to past cases [2].

A typical architecture of case-based reasoning system is shown as the figure below.

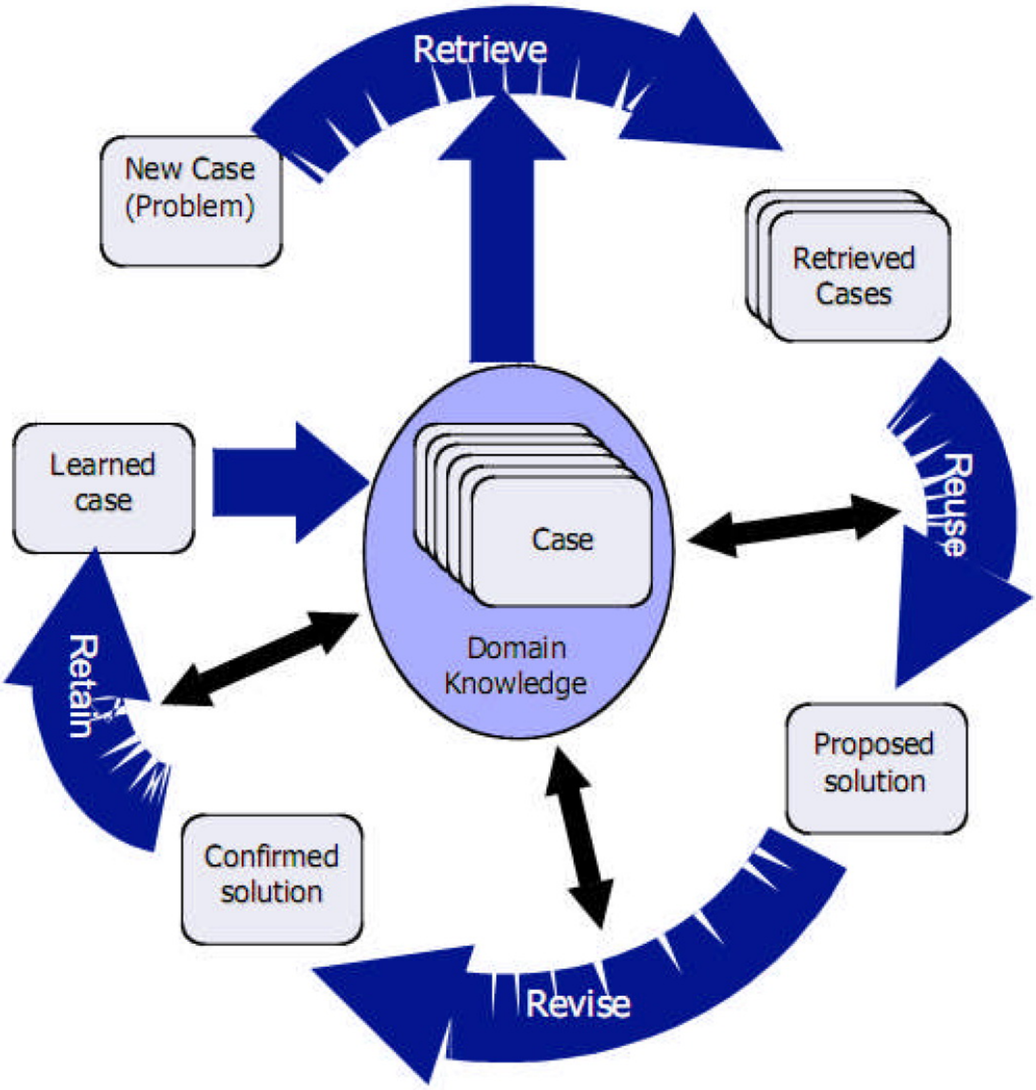


Figure 2-6 Case-based Reasoning System [8]

The case-based reasoning system is a four-step process. The first step of this system is to retrieve the past cases from Domain Knowledge Library to solve a new problem. The case should include the problem, solution, and annotations such as information about the derivation of its solution. The second step is to map the solution from the previous case to solve the new problem after the difference between these two cases were acquired. The new solution is conducted by adapting the old solution to fit the new situation. The third step is to test the proposed solution, and revise the proposed solution if it fails. Lastly, after the proposed solution has been adapted to the target problem successfully, this new solution is retained into Domain Knowledge Library.

A basic premise in case-based reasoning system is that many problems that decision makers encounter are not unique, but rather they are variations of a problem type [2]. This technique is well suited for poorly understood problem areas for which structured data is available to characterize operating scenarios [8].

2.3.2.3 Model-based Reasoning System

Model-based reasoning system is a wide category that describes the use of a broad variety of engineering models as the foundation for the knowledge and the techniques applied for diagnosis [8]. A typical model-base reasoning system is shown below.

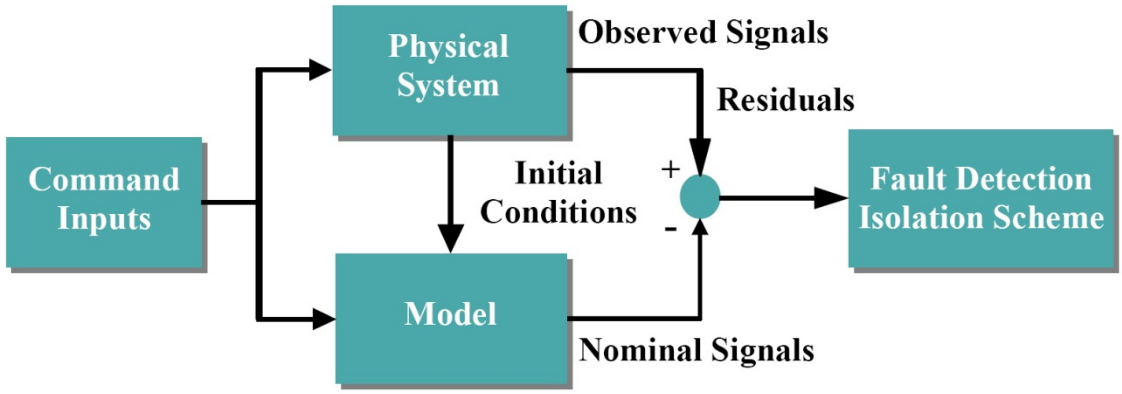


Figure 2-7 Model-based Reasoning System [8]

The model-based approach compares how the system is actually performing to the manner in which the model expects the system to perform given its actual operating conditions [9]. If there is dissimilarity between the physical system and the compared model, an analysis process shall be conducted in order to find and determine the reason for the discrepancy. The accurate and sufficient physical models are required by the model-based reasoning system to enable the full range of operational characteristics to implement the comparison accurately under various conditions.

One of the fundamental advantages of model-based techniques is that, it can be set up such that the model, running with the same inputs/commands as the actual engine, will only predict the nominal outputs [10]. However, a draw-back of model-based reasoning is that it is typically based on static knowledge and is often difficult or expensive to grow with actual experiential data [2].

2.3.2.4 Learning System

Learning system is a data-driven approach which is derived directly from routinely-monitored system operating data [8]. The data-driven approach provides monitoring capability to detect its own model establishing through system data elements. Normally, learning system technique uses the following five steps to implement detection and diagnostic decisions. The first step – high impact malfunction determination is relied on using the past data to understand the types, severity and locations of actual and possible failures. As the second step, data selection, transformation, diagnosis and preparation are the main functions to establish the final database for classification and model sets. After that, data processing is needed to detect trends and degradation, and assess the severity of a failure for early warning. The forth step is testing and validation which ensure the quality of model sets. At last, results fusion method provides higher diagnostic accuracy to predict fault severity and assess the system health condition. The learning systems technique provides the ability to handle highly collinear data of high dimensionality, substantially reduce the dimensionality of the monitoring problem, and compress the data for archiving purposes. However, the main drawback of it is that its efficacy is highly dependent on the quantity and quality of system operational data [8].

2.3.2.5 Discussion

The rule-based expert system will be a good choice for automatically diagnosing situations in which the diagnosis of failure events in a system is a well-known, stable process and expertise exists [8]. Thus, it is very suitable for aircraft fuel system to realize the automated failure diagnosis.

For the diagnosis of mechanical components associated with the fuel temperature, the model-based reasoning system can locate the failed components by comparing the actual and expected performance of fuel system.

In the conceptual design phase of FW-11, the past case and data are unavailable. Therefore, at this stage, the case-based reasoning system and learning system are not suitable for the fuel system PHM development.

2.3.3 Prognosis

For the gradually occurred components/subsystems and health status modes, decisions should be made before the harmful situation occurred. This prediction of the future state is known as prognostics [7]. In PHM, the term “prognostics” includes the broad functions of fault/failure detection and isolation, enhanced diagnostics, material conditions, performance monitoring, and life tracking, rather than just prognosticate functions alone [11]. It means that the prognostic capability, real-time monitoring and diagnostic capability are connected tightly.

In the early time of health management development, the relevant technologies were traditionally focused on failure detection and isolation. As the increasing requirements of condition-based maintenance and low-cost logistics, the concept of the prediction of RUL is introduced into the health management development platform. The main goal of the prognostic technology is to provide a validated prediction of the RUL for either a component or a system. Prognostic system can reduce the overall life cycle costs by decreasing the maintenance cost through the implement of the capabilities presented.

The figure below summarizes the range of possible prognostic approaches as a function of the applicability to various systems and their relative implementation cost [12].

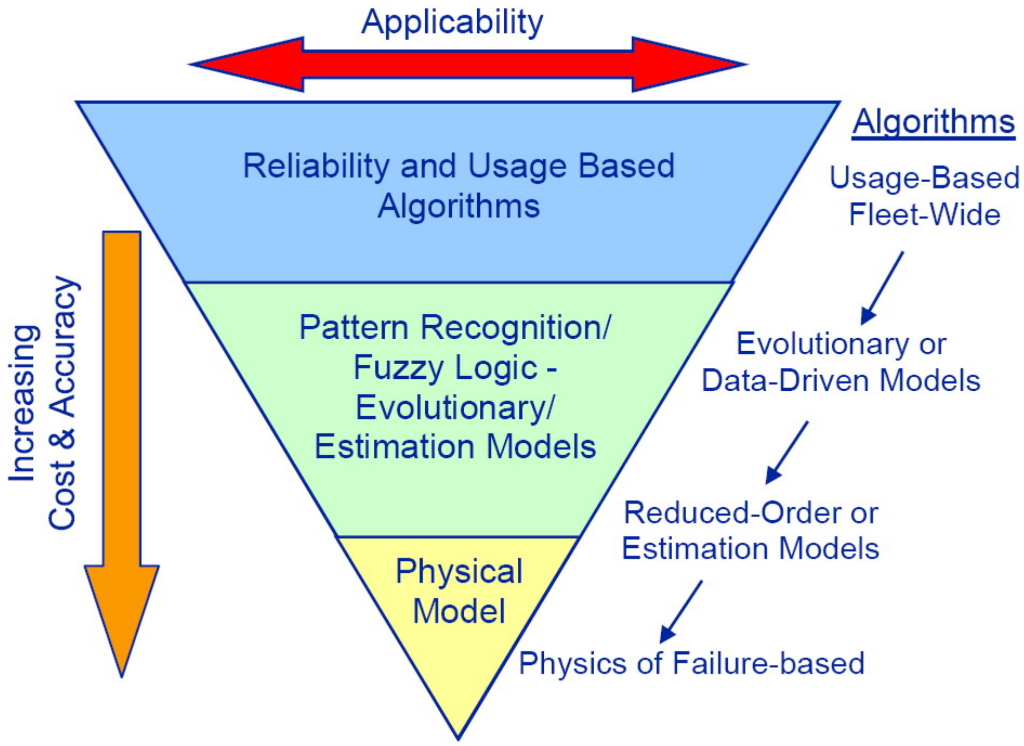


Figure 2-8 Prognosis Technical Approaches [12]

The development of the prognostic technology is based on a variety of techniques such as mathematical methods, probabilistic/statistical methods, artificial intelligence tools, and computational intelligence arena. The following sections describe five mainly used prognostic approaches.

2.3.3.1 Statistical Reliability and Usage-based Approach

Statistical reliability and usage-based approach is a historical data-based method which needs the historical statistics of component or LRU failure and operational usage profile, sometimes along with the relevant failure rate statistics. Typically, failure and/or inspection data is compiled from legacy systems and a Weibull distribution or other statistical failure distribution can be fitted to the data [12].

The statistical reliability and usage-based approach is an appropriate method to achieve the prognostic capability for the components which have very low failure rates or low failure severity level, have few or no sensed data associated with.

2.3.3.2 Trend-based Evolutionary Approach

Trend-based evolutionary approach relies on the comparison between the failure damage probability model based on the historical data and the current multi-parameters probability state space to implement the detection of current health condition and the analysis of trend deviations. In other words, this method is to use the interface between the current parameters probability space and the known damage probability space to conduct the quantitative inference.

Generally, trend-based prognostics works well for system level degradation because conditional loss is typically the result of interaction of multiple components functioning improperly as a whole [12].

2.3.3.3 Data-driven Model-based Approach

In many cases, the historical or statistical data is difficult to be obtained. Or in other instances, even though the sufficient statistical or failure database is available for a component or system, it is still difficult to complement the prediction of failure progression. In such situations, data-driven model-based approach will be a reasonable choice. Data-driven model-based approach provides a nonlinear network method which uses some specific algorithms set in the calculation model to obtain the prediction outputs related to the failure condition. Figure 2-11 shows an example of this prognostic approach.

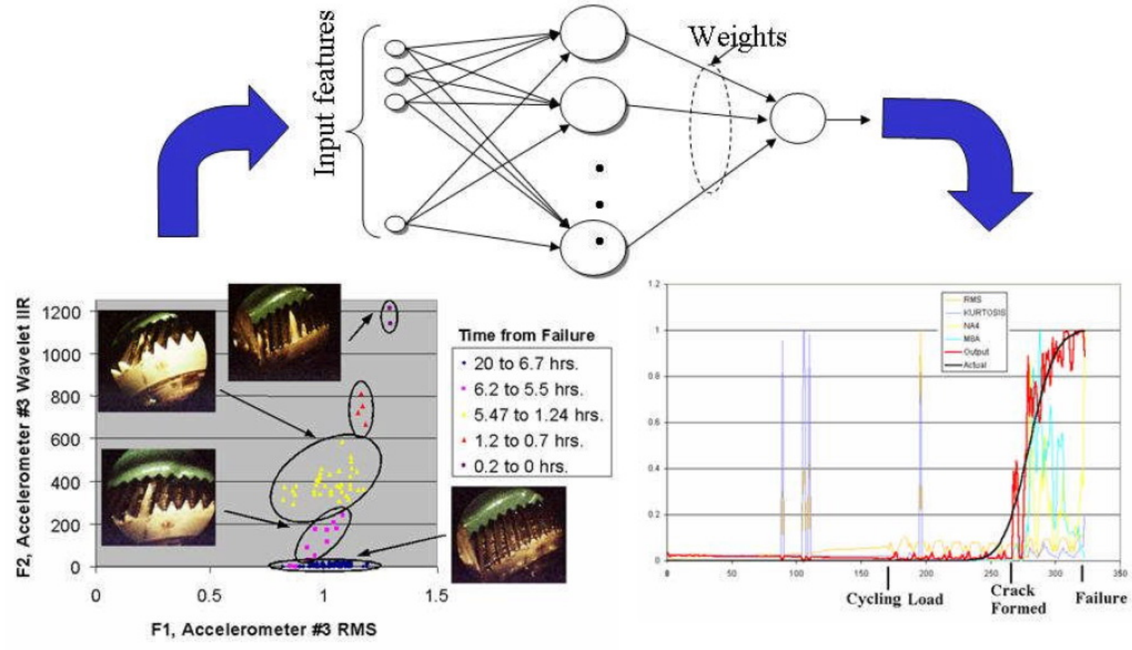


Figure 2-9 Data-driven Model-based Approaches [12]

2.3.3.4 State Estimator Based Approach

State estimator based approach is based on the tracking filter technique to enable the prognostic capability. It is a dynamical systems tool for estimating unknown states by combining current measurements with the most recent state estimate [12].

This approach can be regarded as a virtual sensor in which currently available sensor measurements are taken to provide optimal estimates of quantities of interest which cannot be measured directly [12]. It can be used in not only a linear system, but also a nonlinear system by some specific filter algorithms.

2.3.3.5 Physics-based Modelling Approach

Differing from the prognostic techniques above, physics-based modelling approach is a complicated and comprehensive modelling method so as to estimate the failure mode progression for a component or system. Physics-based modelling approach is a combination or fusion of the feature-based and model-based approaches provides full prognostic ability over the entire life of the component, thus providing valuable information for planning which components to inspect during specific overhauls periods [12]. It also integrates the physical modelling method and stochastic modelling technique to provide the prediction output of the RUL for a component or system.

2.3.3.6 Discussion

To perform the prognostic function, the historical data are required by the former two approaches. However, in the conceptual design phase of FW-11, there is no historical data available. Thus, neither the statistical reliability and usage-based approach nor the trend-based evolutionary approach is reasonable at this stage.

State estimator based approach is mainly used to estimate the unknown states of components or system. Physics-based modelling approach focuses on the prognosis of RUL of component or system. These two approaches are not suitable for the fuel temperature prediction.

By using specific algorithms set in the calculation model, the data-driven model-based approach can predict the fuel temperature trends during flight. The fuel temperature prognostic function will be achieved through this approach.

2.4 Fuel Temperature Prediction

The open of four cross-polar routes is an important development for the long range civil aviation transport. These routes provide reducing in time and fuel so as to have great advantages on the environment. Due to the extremely cold weather in the polar region, the long time exposure of aircraft fuel tanks to the low outside temperature may cause the fuel temperature drops close to or below the fuel freezing point (FFP). Both Boeing and Airbus have designed software to aid the flight crews in addressing the cold fuel or fuel freezing issues at the flight planning stage for a given route [20].

Take the Airbus's fuel temperature prediction software for example: the software accepts inputs such as performance (altitude, speed, fuel on Board), navigation information (waypoints, time, distance) and weather forecast (temperatures) to predict the fuel temperature in each fuel tank during the flight, then the warnings and advisories will be provided to the pilots [13]. The fuel temperature prediction software can advise the pilots to fly faster or fly lower in order to avoid the freezing fuel issues.

2.5 Conclusions

PHM system is to assess the health status of the vehicle or system, provide diagnosis and prognosis of system faults and deliver recommendations for remediation [14]. The concept of PHM is revolutionary and pushes the state-of-the-art in logistics and maintenance management [15]. The PHM system should incorporate a philosophy, methodology and process that focus on design and development for safety, operability, maintainability, reliability and testability [16]. There are some PHM systems have been developed and put into practice, however, more accurate, reliable and automated health management technologies are highly needed because of the uncertainties in the current complex system or aircraft.

In order to deploy the PHM system to aircraft fuel system, three primary functions need to be achieved: detection/monitoring, diagnosis and prognosis. Therefore, the key parameters and crucial components which have great impacts to the system performance need to be identified by using FHA and FMEA.

In this chapter, four diagnostic techniques have been discussed briefly. Each method has its own advantages and disadvantages. The former two techniques require many diverse domain knowledge based on engineering experiences. The latter two systems need a great amount of accurate physical model and operating data of a system. After the comparison of these four techniques, the rule-based expert system and the model-based reasoning system are more suitable for the fuel system PHM development.

As a new and crucial element of PHM system, the current prognostic technique mainly focuses on the indication of the failure mode progression and the prediction of the RUL for specific components or subsystems. However, the crucial parameters which have great impact to the safety during flight also should be monitored, diagnosed, and prognosticated.

Five widely used prognostic approaches are introduced in this chapter. Each approach has its own characteristics. After considering the type of prognostic target and the progress of FW-11, the data-driven model-based approach is chosen to predict the fuel temperature during flight.

3 Fuel System of FW-11

In order to deploy the fuel system PHM technology to the FW-11 to increase its competitiveness, an assumed fuel system should be designed firstly. All research works in this thesis depend on this assumed fuel system. Base on the assumed fuel system, the FHA, FMEA and FTA are conducted to find out the failure modes and effects of this fuel system. Furthermore, the fuel temperature PHM architecture can also be established.

The FW-11 is a long range point to point civil aircraft, which basic seat is 248 and design range is 7500 nautical miles. More details of FW-11 are addressed in Appendix A. According to the General Requirements of FW-11, the minimum requirements for the FW-11 are airworthiness regulations from FAA, EASA and CAAC, correspondingly, the fuel system design should meets these regulations at least.

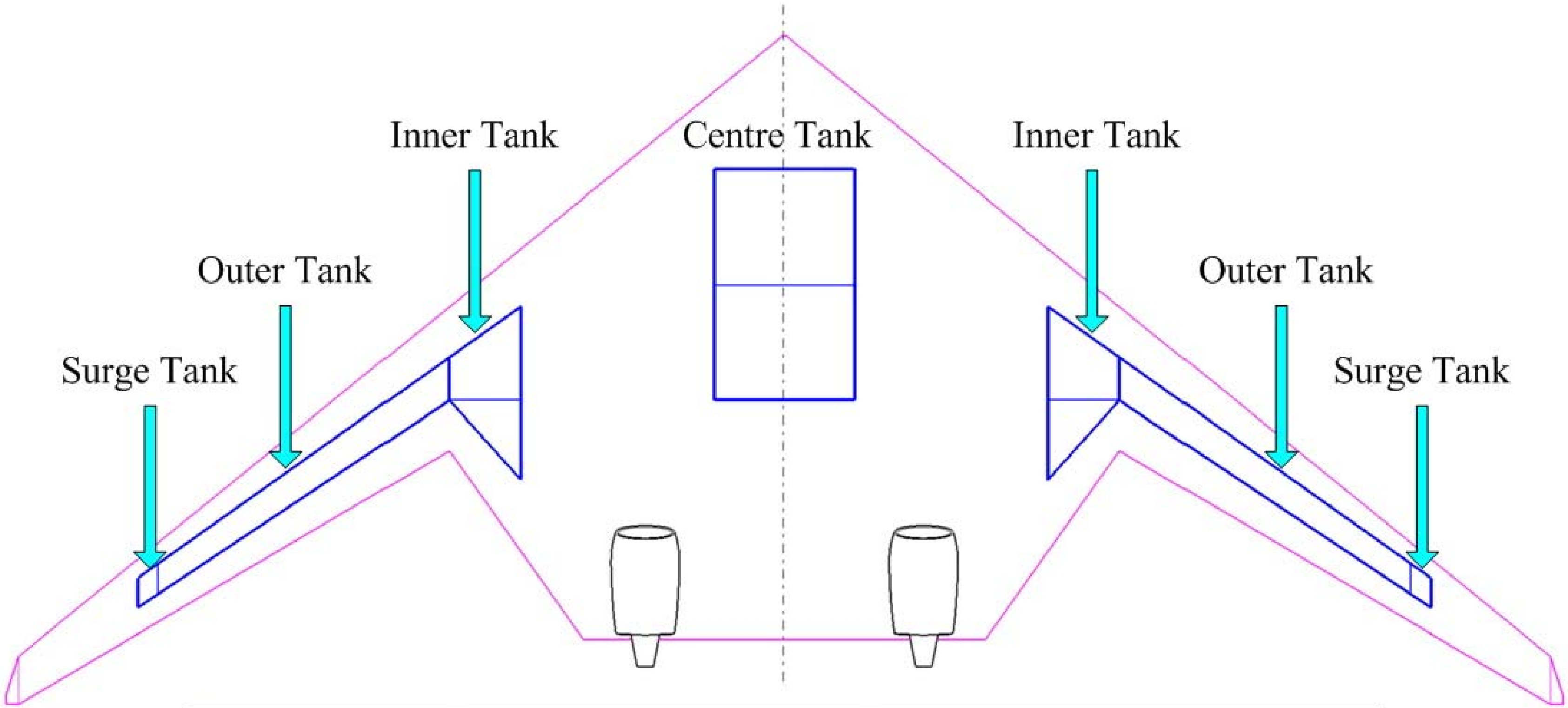
3.1 Fuel System Architecture

The primary functions of the fuel system are to store enough fuel required by the mission and to supply fuel to the engine and Auxiliary Power Unit (APU) at proper rate, pressure and temperature under any operating conditions safely and continuously. During the mission, the fuel system should maintain the CG of aircraft within designated range. The fuel in the fuel tank can also be used as heat sinks to cool down other systems or components.

The fuel system of FW-11 consists of 6 subsystems which are shown as below:

1. Storage subsystem;
2. Fuel feed (engine and APU) subsystem;
3. Refuel/defuel subsystem;
4. Fuel jettison subsystem;
5. Vent/ Inerting subsystem;
6. Fuel indication and management subsystem.

These subsystems are shown in the following figures.



Tank	Fuel Capacity (kg)	Max. Fuel Capacity (kg)
Centre Tank	36940	60980
Inner Tank	12250×2	12250×2
Outer Tank	5650×2	5650×2
Total	72740	96780

Figure 3-1 Fuel Storage Subsystem

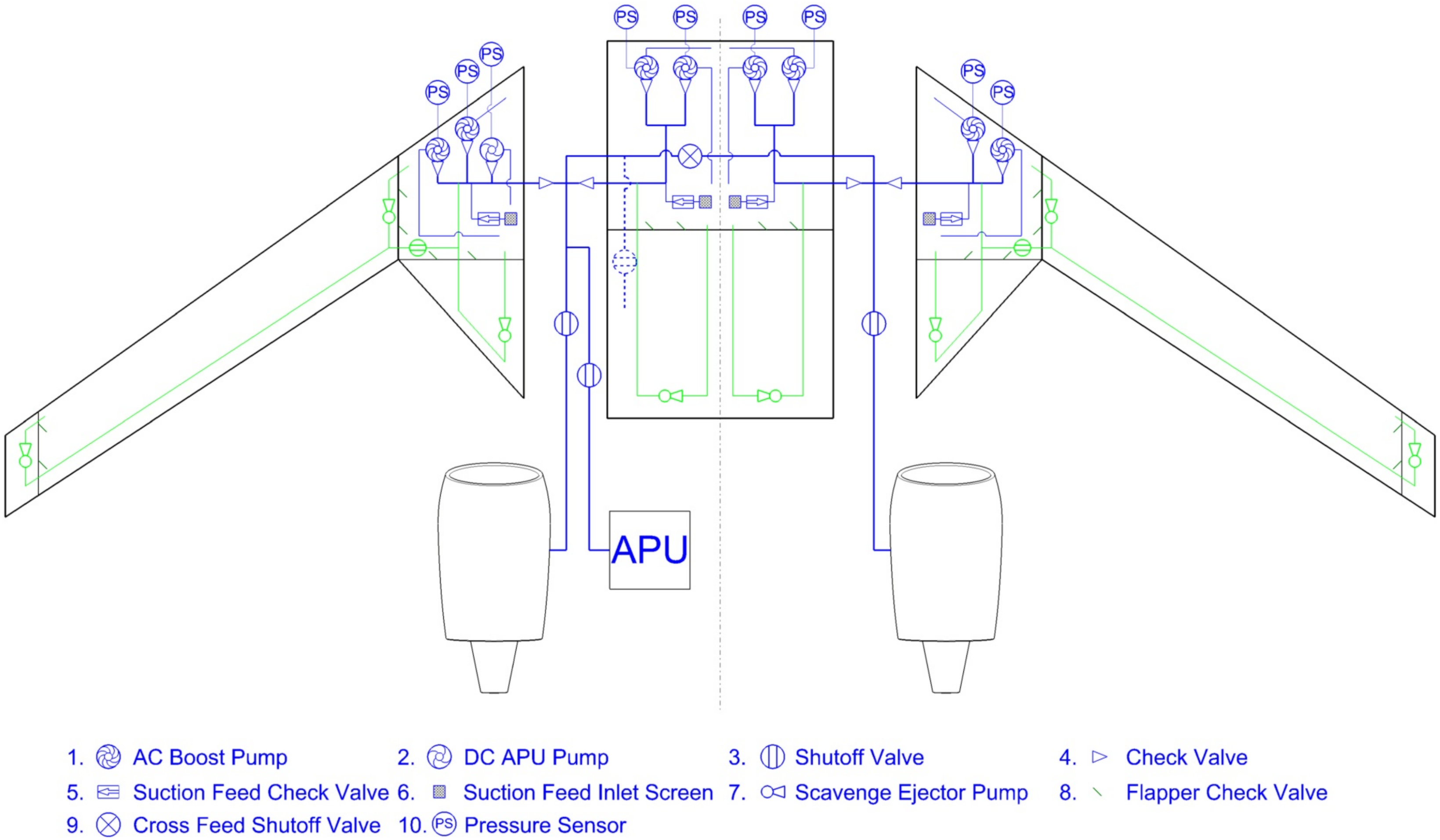


Figure 3-2 Fuel Feed Subsystem

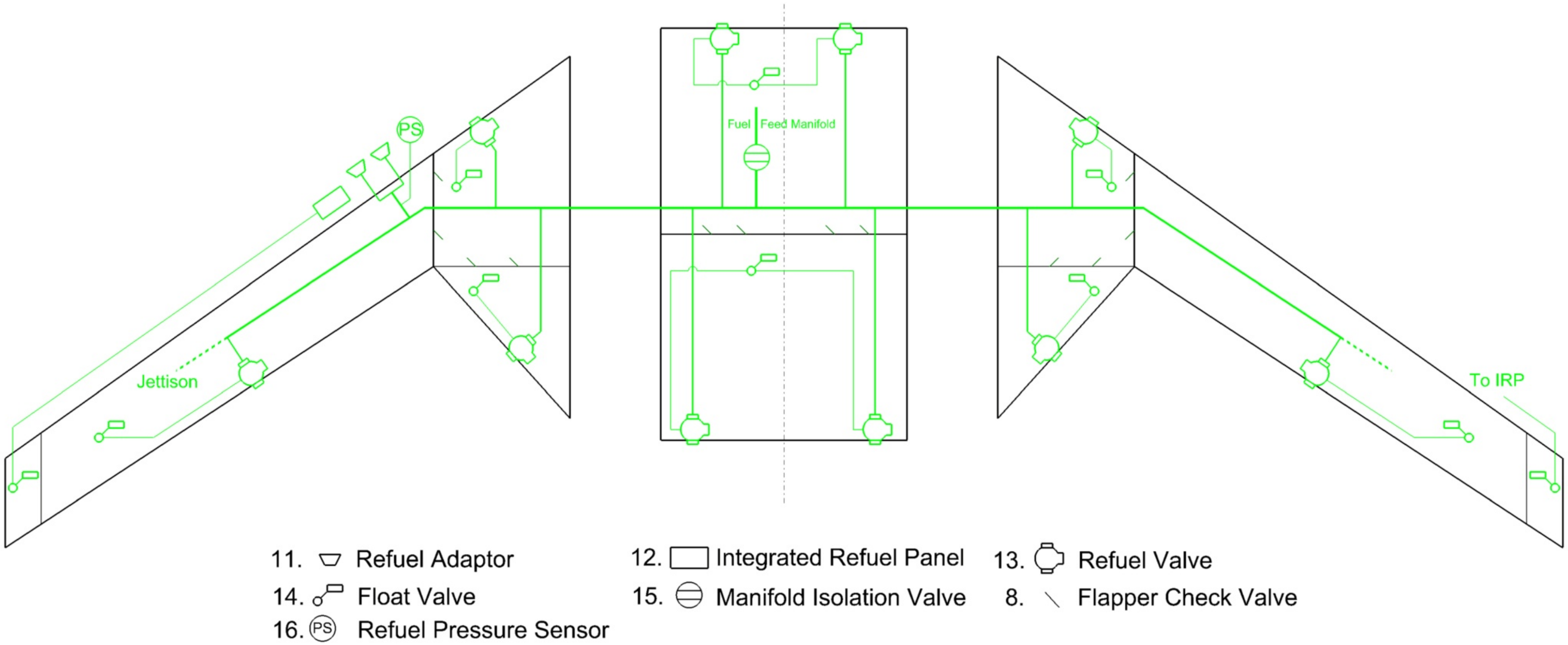


Figure 3-3 Refuel/Defuel Subsystem

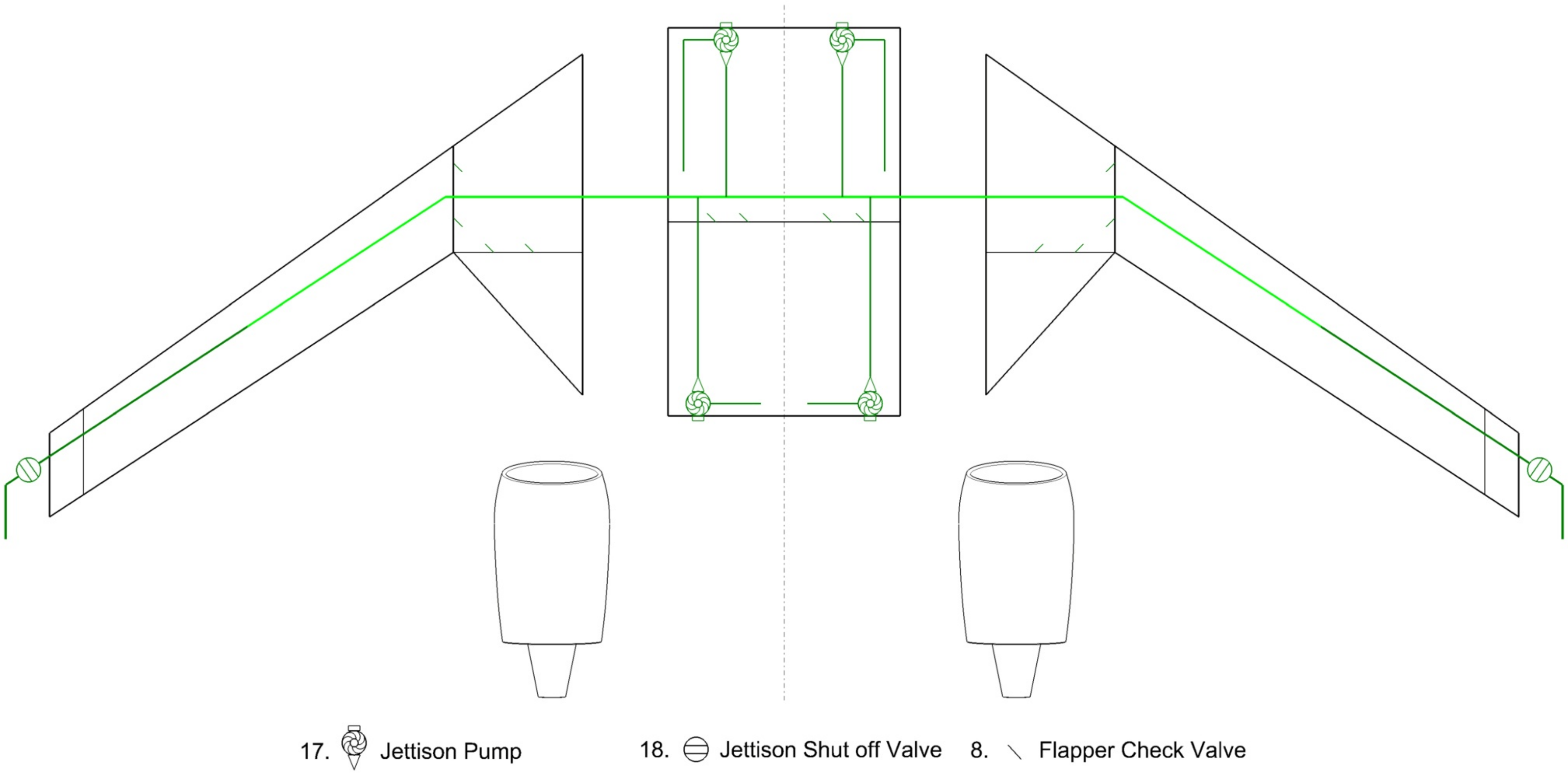


Figure 3-4 Fuel Jettison Subsystem

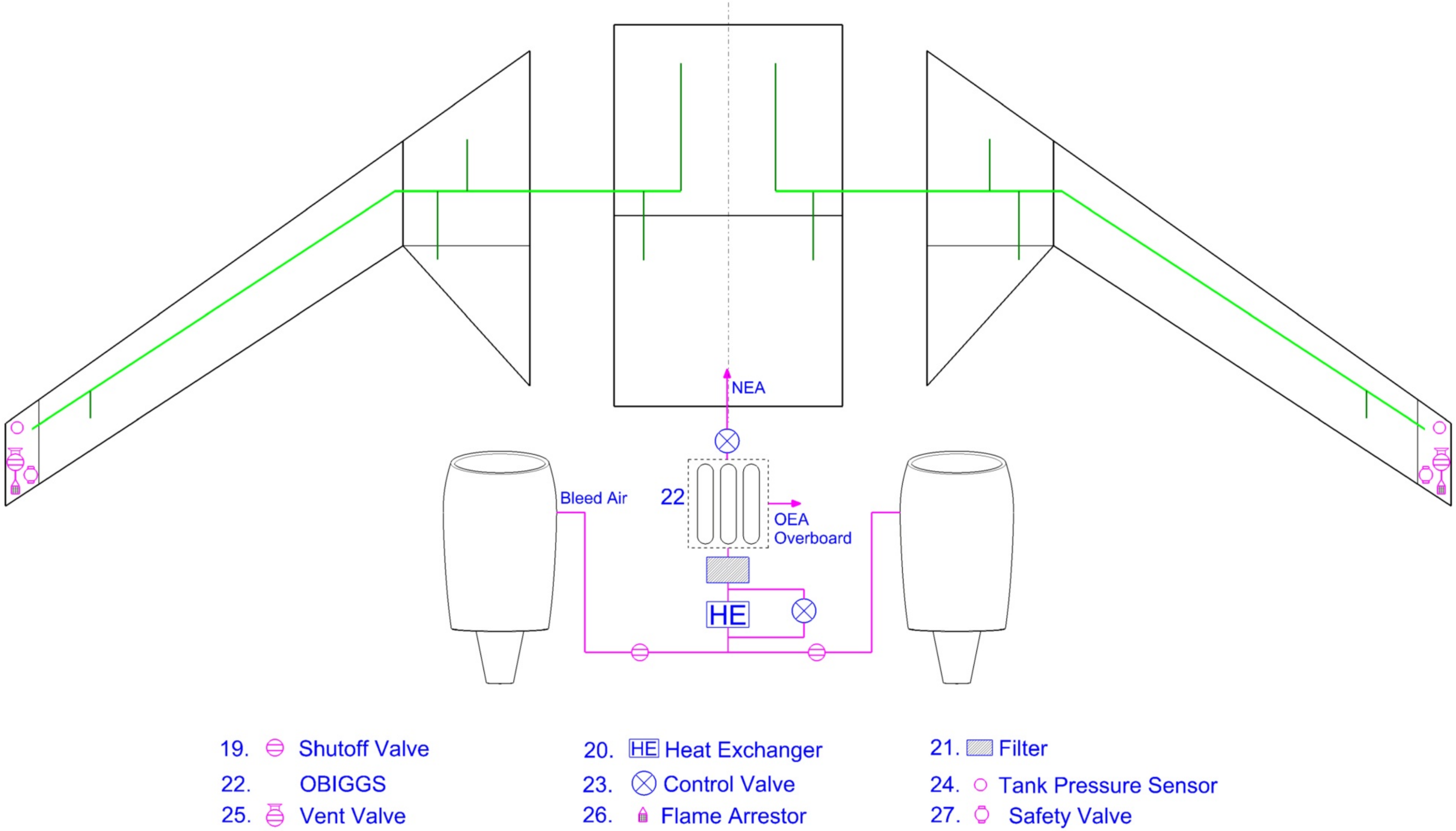


Figure 3-5 Vent/Inerting Subsystem

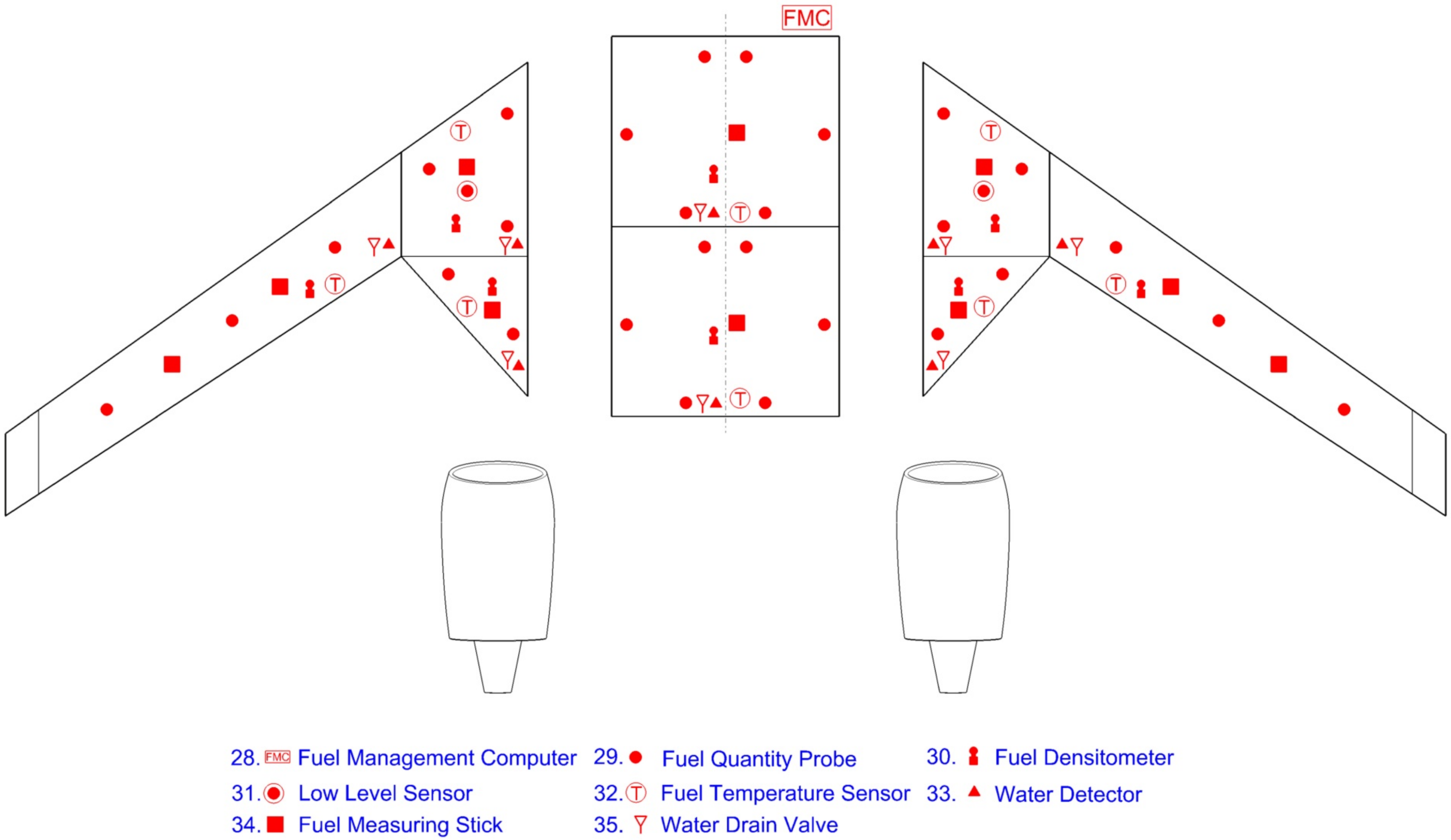


Figure 3-6 Fuel Indication and Management Subsystem

All components which are used in the assumed fuel system are shown in Table 3-1.

Table 3-1 List of Components

Item	Components	Item	Components
1	AC Boost Pump	19	Shutoff Valve
2	DC APU Pump	20	Heat Exchanger
3	Shutoff Valve	21	Filter
4	Check Valve	22	OBIGGS
5	Suction Feed Check Valve	23	Control Valve
6	Suction Feed Inlet Screen	24	Tank Pressure Sensor
7	Scavenge Ejector Pump	25	Vent Valve
8	Flapper Check Valve	26	Flame Arrestor
9	Cross Feed Shutoff Valve	27	Safety Valve
10	Pressure Sensor	28	Fuel Management Computer
11	Refuel Adaptor	29	Fuel Quantity Probe
12	Integrated Refuel Panel	30	Fuel Densitometer
13	Refuel Valve	31	Low Level Sensor
14	Float Valve	32	Fuel Temperature Sensor
15	Manifold Isolation Valve	33	Water Detector
16	Refuel Pressure Sensor	34	Fuel Measuring Stick
17	Jettison Pump	35	Water Drain Valve
18	Jettison Shut off Valve		

3.2 Fuel System Functions

The target of this section is to illustrate the operational functions of the assumed fuel system for the following FHA, FMEA and FTA application. The primary function of the assumed fuel system is to supply a continuous fuel at proper rate, pressure and temperature to the engines and APU safely under any designated operating conditions. The detail functions of storage and fuel feed sub-systems are discussed in the following parts.

3.2.1 Storage Subsystem

The fuel storage subsystem is primarily used to holds the fuel necessary for both engines and APU operation. It should have enough strength to maintain the designated relative pressure to the outer atmosphere. It also provides maintenance access to the ground crews and helps them to drain the fuel tanks.

As shown in Figure 3-1, the storage subsystem of FW-11 comprises five fuel tanks: Centre Tank, two Inner Tanks and two Outer Tanks. The total design fuel capacity and the maximum fuel capacity are 72740kg and 96780kg respectively.

The Centre Tank is located under the cabin floor and surrounded by double wall structure, a spanwise beam divides it into two parts: Forward Tank and Aft Tank. The Forward Tank is used as the collector tank, into which the fuel is delivered before being fed to the engines or APU. There are flapper check valves installed in this beam, permit the fuel flow from Aft Tank to forward by gravity in case of ejector pump failure but prevent fuel flow to the reverse direction. A set of overflow ports are located in the top of the spanwise beam to let redundant fuel flow back to Aft Tank so as to protect the collector tank.

Both Outer and Inner tanks are integral fuel tanks. The left side and right side are symmetrical, for convenient, the left side is selected as an example to illustrate the fuel tank configuration. The Outer Tank is in the outer wing box of the outer wing, and the Inner Tank is in the inner wing box of inner wing. The Outer Tank and Inner Tank are partly isolated by structural rib, in which flapper check valves are installed to permit fuel flow from outboard tank to inboard tank by gravity but prevent fuel flow to the reverse direction. A set of overflow ports are located in the top of the rib to let redundant fuel flow back to Outer Tank so as to protect the Inner tank.

The Inner tank is separated into Forward Inner Tank and Aft Inner Tank by a spanwise beam. The previous tank is used as collector tank to receive fuel flow from Aft Inner Tank and Outer Tank. Similarly, flapper check valves are installed in this beam to permit the fuel flow from Aft Tank to Forward Tank by gravity in case of ejector pump fails but prevent fuel flow to the reverse direction. This beam is a bulkhead so that the fuel in the collector tank cannot back to the Aft Inner Tank.

An adjacent surge tank is outboard of each Outer Tank. Surge tanks collect fuel overflow from outer tank in case of aircraft manoeuvre. The fuel overflow drains into the outer tanks through ejector pump located in the surge tanks or the check valves in the bottom of structural rib by gravity.

There are heat exchangers in each collector tank to sink the heat from inerting subsystem and hydraulic system.

3.2.2 Fuel Feed Subsystem

As shown in Figure 3-2, a cross feed shutoff valve divide the fuel feed subsystem into left and right fuel feed lines to make sure each side feeds the engine independently. During normal operation, the cross feed shutoff valve remains closed to isolate the left and right fuel feed lines. The cross feed shutoff valve could open to provides fuel from both tanks to one engine in case of one engine malfunction or provides fuel to both engines from one side fuel tank when there is a lateral imbalance.

The fuel feed subsystem consists of two AC boost pumps per inner tank and another two AC boost pumps in the centre tank for engines in each side respectively. Each AC boost pump is fully capable of maintain fuel flow to one engine and provide motive flow to the connected ejector pumps in case of a single pump failure. A DC pump is installed in the left inner tank for the APU and engine start, it could be shut off when the AC boost pumps are working.

There are shutoff valves in each engine and APU fuel feed lines to shut off fuel flow into the fire zones in case of engines and APU catching on fire.

Ejector pumps are used to minimize unusable fuel and scavenge condensed water to the collector tanks. They are installed in the lower point of the other fuel tanks except the collector tanks and are operated by the motive flow supply provided from the AC boost pump(s).

The fuel consumption order is shown as below:

1. Centre tank - should be consumed first for safety consideration, the fuel would be jettisoned when crash landing occurred or for landing weight reduction if necessary.
2. Aft Inner Tank – after the exhaustion of centre tank, this tank will be consumed for the Centre of Gravity (CG) adjustment consideration.
3. Outer tank – this tank is the next-to-last tank since the fuel in the outer tank can unload the wing.
4. Forward Inner tank – this tank is used as collector tank so that it is consumed lastly.

3.2.3 Refuel/Defuel Subsystem

The refuel subsystem is used to transfer fuel required by the mission from the refuel adapters, which connect to the ground pressure refuelling system directly, to the fuel tanks. Contrary, the defuel subsystem moves fuel from the aircraft fuel tanks to the ground refuel station, or from one fuel tank into another.

There is a refuel station on the leading edge of left wing of FW-11, outboard of the Inner Tank. It has two refuel adapters and an Integrated Refuel Panel (IRP). FW-11 employs ten hydro-mechanical refuel valves which are shown in figure 3-3. The valves are mounted on the spar, of which bodies are inside the fuel tanks and actuators are outside the fuel tanks.

There are two modes can be chosen for the pressure refuelling of FW-11: automatic mode or manual mode. Both modes require the vent valve open to vent the fuel tank or excess fuel while refuelling the aircraft. There is no gravity refuelling adaptor in FW-11 since it will take too much time for the refuelling of the enormous amount of onboard fuel. This configuration is similar to Boeing 777.

In the automatic mode, the total quantity fuel need to be loaded is entered in the Fuel Management Computer (FMC) through the Integrated Refuel Panel. The FMC uses this input to control the refuelling of each tank so that the fuel is refuelled into the fuel tanks automatically. Each surge tank has a float shutoff valve to shut off all the refuel valves by sending signals to the IRP to remove power from all the refuel valves when there was overfill fuel entered the surge tank.

In the manual mode, the operating statuses of the refuel valves are controlled by the refuel valve switches on the IRP and then refuel each tank to a desired quantity. Fuel quantity measuring sticks are equipped in the bottom of each tank for the fuel quantity indication when there was no display on the IRP. A high-level float shutoff valve is installed in each tank to close the relative refuel valve(s) if the fuel level reached the designated level to protect the fuel tanks.

To defuel the fuel tanks, the fuel pumps are used to pump the fuel out of the tanks to the refuel/defuel manifold tubes, flow across the refuel valves in each tanks, finally enter into the ground tanks or defuel trucks through the refuel adaptors. The refuel/defuel subsystem also can transfer fuel from one tank to another by open the appropriate pumps and applicable refuel valves. The cross feed valve and manifold isolation valve must open to transfer the fuel in the right inner or right outer tank to other tanks through the engine feed manifold.

3.2.4 Fuel Jettison Subsystem

The fuel jettison subsystem dumps fuel overboard to reduce the landing weight or empty the centre fuel tank to protect the passengers whilst crashing landing occurred. The fuel jettison subsystem is shown in figure 3-4.

There are two jettison pumps in the Aft Centre Tank and collector tank to jettison the fuel in these tanks respectively. Normally, the jettison pumps in the Aft Centre Tank are used to reduce the landing weight. The jettison pumps in the collector tank will operate while crashing landing occurred. Each pump has a pressure switch that sends a signal to the FMC for fault indication.

Two fuel jettison nozzle valves are installed near the tips of outer wing, outboard the surge tank. During jettison operation, these valves are open to overboard the fuel. One valve failure will not cause the loss of jettison function.

3.2.5 Vent/ Inerting Subsystem

The fuel vent subsystem keeps the appropriate relative pressure of the fuel tanks to the outside atmosphere throughout the aircraft operational fight envelope since a large pressure difference can damage the fuel tank structure. An 'open vent system' is commonly used in the civil airliners to connect the upper space in the fuel tank to the outer atmosphere.

The FAA issued Special Federal Aviation Regulation (SFAR) 88 in April 2001, applicable to aircrafts registered in the USA [24]. A similar document – JAA INT/POL 25/12 was produced by the Joint Aviation Authorities (JAA), mandatory for all airbus aircrafts [25]. These documents categorise the centre fuel tank as hazardous since this fuel tank is near the air conditioning units which represent a significant heat source to the fuel temperature. Thus, the centre fuel tank inerting is required.

The fuel vent/inerting subsystem of FW-11 keeps the appropriate relative pressure of the fuel tanks to the outside atmosphere and by inerting the airspace in the fuel tanks to protect the fuel tanks. The inerting gas is obtained from an On-Board Inert Gas Generating System (OBIGGS). Figure 3-5 shows the vent/inerting subsystem.

Each fuel tank is vented to a surge tank outboard the outer tank. A vent valve is installed in each surge tank to allow a direct air connection between the fuel tank ullage space and the outer atmosphere during the refuelling operation or in the event of the innerting system malfunction, or aircraft descended dramatically. There are flame arrestors in the vent ports to make sure that a flame does not come inside the fuel tanks through the vent subsystem. A safety valve and an anti-vacuum valve are installed in each surge tank to relief the pressure difference or negative pressure in the fuel tank.

3.2.6 Fuel Indication and Management Subsystem

The fuel indication subsystem has these functions: indicating the fuel quantity, indicating the water in the fuel tank, indicating the fuel temperature, and indicating the fuel pressure.

The fuel management subsystem are used to monitor the fuel system status and control the fuel system operation based upon plenty of pumps, valves, probes, sensors and switches controlled by the FMC.

Fuel indication and management subsystem of FW-11 is shown in figure 3-6.

A set of fuel quantity probes are installed to measure the fuel volume of each tank, the number of fuel probes is needed to be determined. There is a fuel densitometer used as the compensator in each tank to measure the fuel density. The fuel probes and densitometers send signals to the FMC to calculate the fuel quantity, and then the FMC sends both the total fuel quantity and individual tank quantities to the IRP and Engine Indication and Crew Alerting System (EICAS) so as to control the refuel operations and alert the crews respectively.

A low level sensor is located in each collector tank to warn the pilots through the EICAS.

Each fuel tank has a water detector at the low point in the tank sump area to monitor the water accumulation. Each fuel tank also has a fuel temperature sensor to gauge the fuel temperature.

There is a fuel pressure switch installed in the outlet of each fuel pump, before the check valve in the flow direction. These fuel pressure switches are used to send low pressure signals to the FMC in case of fuel pump malfunction.

3.3 Conclusion

In this chapter, the fuel system architecture for FW-11 has been constructed according to the design requirements. The operational principle has also been defined to conduct the failure modes of fuel system. It provides foundation to the following FHA, FMEA and FTA analyses.

4 Fuel System Study

The following paragraphs discuss the results of fuel system FHA, FMEA and FTA for the assumed fuel system of FW-11 stated in the previous chapter.

4.1 Fuel System FHA

4.1.1 Introduction

This section is to perform a comprehensive investigation of the fuel system functions, and to find out the fuel system failure conditions which were classified into four hazard class: catastrophic, hazardous, major and minor. The primary functions of the fuel system are to store enough fuel required by the mission and to supply fuel to the engine and APU at proper rate, pressure and temperature under any operating conditions safely and continuously.

Based on the FHA results, more in-depth analyses such as FMEA could be conducted. According to the fuel system functions derived from chapter 3 and SAE ARP 4761 [18], a set of FHA tables could be constructed.

4.1.2 Failure Condition Severity and Effect Classifications

To evaluate the worst possible effects caused by product malfunction, the severity classification of each potential failure mode should be defined. The severities of failure condition and effect classifications which are used in this thesis are shown in the table below.

Table 4-1 Failure Condition Severity and Effect Classifications [19]

Failure Condition Severity	Failure Condition Effect
Minor	Failure conditions that would not significantly reduce airplane safety and which involve crew actions that are well within their capabilities.
Major	Failure conditions which would reduce the capability of the airplane or the ability of the crew to cope with adverse operating conditions to the extent that there would be, for example, a significant reduction in safety margins or functional capabilities, a significant increase in crew workload or in conditions impairing crew efficiency, or some discomfort to occupants.
Hazardous	Failure conditions which would reduce the capability of the airplane or the ability of the crew to cope with adverse operating conditions to the extent that there would be: I - A large reduction in safety margins or functional capabilities; II - Physical distress or higher workload such that the flight crew cannot be relied upon to perform their tasks accurately or completely; or III - Serious or fatal injury to a relatively small number of the occupants.
Catastrophic	All failure conditions which would prevent continued safe flight and landing.

4.1.3 Fuel System FHA Summary

The detail FHA results of the assumed fuel system of FW-11 are shown in Appendix B. Since the catastrophic events have great influence to the flight safety and system performance, the failure conditions related to these severe events are summarised here for the following research. The catastrophic failure conditions of the assumed fuel system are shown as Table 4-2.

This table shows clearly that the failure of fuel feed subsystem, fuel storage subsystem are more serious than other subsystems. Obviously, the research should focus on the study of these subsystems, especially the cause of these failure conditions.

Table 4-2 Overview of the Fuel System Severe Failure Condition

Failure Condition	Severity
Loss of pressurized fuel flow to both engines	Catastrophic
Fuel tank explosion	Catastrophic
Unable to shut off fuel feed flow to a nacelle in event of catching fire	Catastrophic
Unable to shut off fuel feed to APU in event of catching fire	Catastrophic

4.2 Fuel System FMEA

4.2.1 Introduction

The FMEA is an analysis approach, which should be conducted in the early design stage to evaluate the design and to provide foundation for the establishment of corrective action priorities. FMEA shall documents all possible failure in the system, determines the effects of each failure on system operation according to the failure mode analysis, identifies the causes of each single failure, and ranks the severity of each failure. FMEA is a bottom-up approach that traces the effects of crucial component failures through the system [8].

4.2.2 FMEA Process

The FMEA is one of the important analysis methods of product security, reliability and maintainability plan. This analysis method is used to determine the potential effects which each failure had on system security, perform mission, system performance, maintainability requirement by analyzing all the possible failure modes. Then, to classify every potential failure by its severity in order to acquire the evidence of establishing design, improving process and compensating provisions.

When analyse certain product failure mode, the failure shall be considered as the only failure in the system. If a certain mode is undetected, the effects of other related failure shall be analysed further because these failures and the undetected failure maybe bring on catastrophic or hazardous events. To start this process, the engineer defines the system to be analysis. This may be done by drawing a scheme diagram that shows how the system shall perform [17]. It also includes the function description of each system and various operational modes. If more than one method of performing a specific function is supplied, the alternative operational modes shall be defined. Simultaneously, the required mission time of each function shall be identified, which is developed for products to operate in different operational modes during various mission phases.

FMEA normally begins at the component level [17]. The key step of the FMEA is to complete the FMEA worksheet. Typically, a FMEA worksheet contains several basic elements as follows:

1. The name of the components being analysed;
2. A brief description of how they shall function;
3. A list of the ways in which they can fail;
4. A description of the effects that these failures have no higher assemblies of the system;
5. Means available for detecting the failure or compensating for the effects of the failure;
6. An assessment of the severity of the failure.

4.2.3 Fuel System FMEA Summary

The FMEA in this thesis is based on the assumed fuel system of FW-11. The detail result of FMEA for each component is listed in Appendix C.

4.3 Fuel System FTA

4.3.1 Introduction

The FTA for the fuel system of FW-11 is discussed in the following sections. FTA is a top-down approach in which undesirable events are studied to determine all possible causes of that event [8]. It focuses on a particular unexpected top event and provides a method to identify the causes of this event.

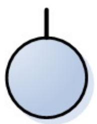
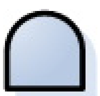
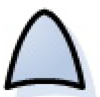
The FTA is depended on the FHA and FMEA results. It should include all the failure modes and events which contribute to the failure condition instead of only focusing on the fuel system.

Since the FW-11 is in the conceptual design stage, the failure rate and mission time cannot be clarified or confirmed, the probability of basic and top event is not included in this thesis.

4.3.2 FTA Symbols

A set of symbols are used in the FTA to provide visual representation of the causes and combinations of causes that lead to the top event. The symbols are defined below.

Table 4-3 FTA Logic Symbol

Symbol	Name	Description
	Event	Including top event and intermediate event
	Basic event	Event which requires no further development
	AND-gate	Event occurs only if all next lower events occur
	OR-gate	Event occurs if any next lower event occurs
	Transfer	To connect the inputs and outputs of related fault trees

4.3.3 Fuel System FTA Results

The detail FTA results of the catastrophic failure conditions are shown below.

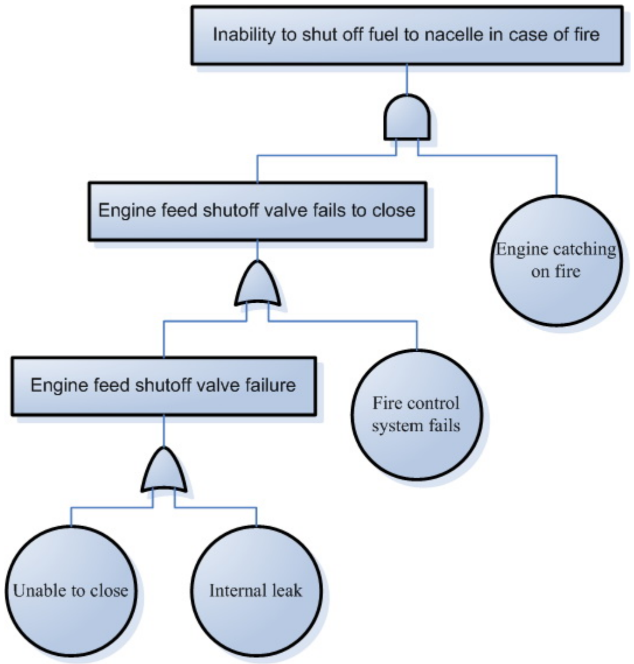


Figure 4-1 Unable to Shut off Fuel Feed to a engine While Catching Fire

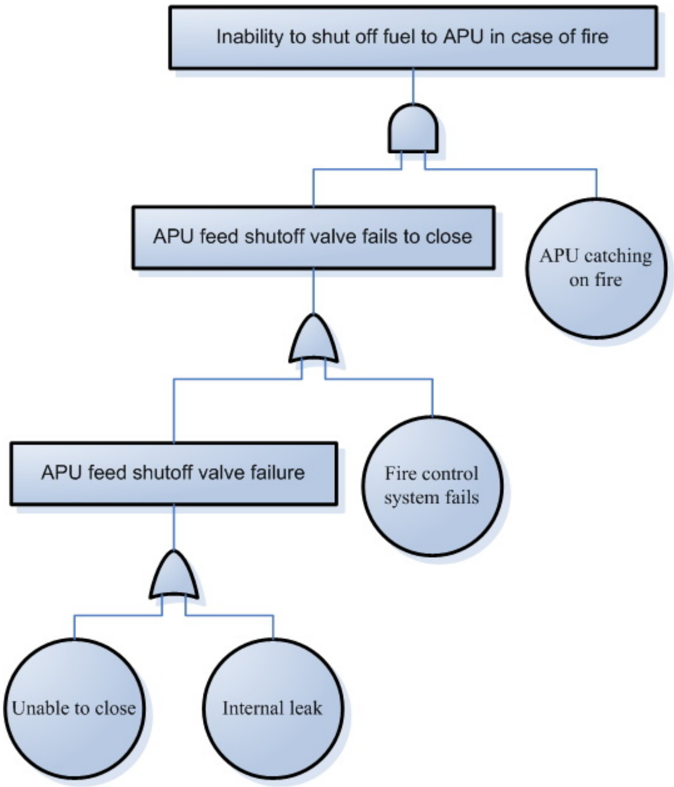


Figure 4-2 Unable to Shut off Fuel Feed to APU While Catching Fire

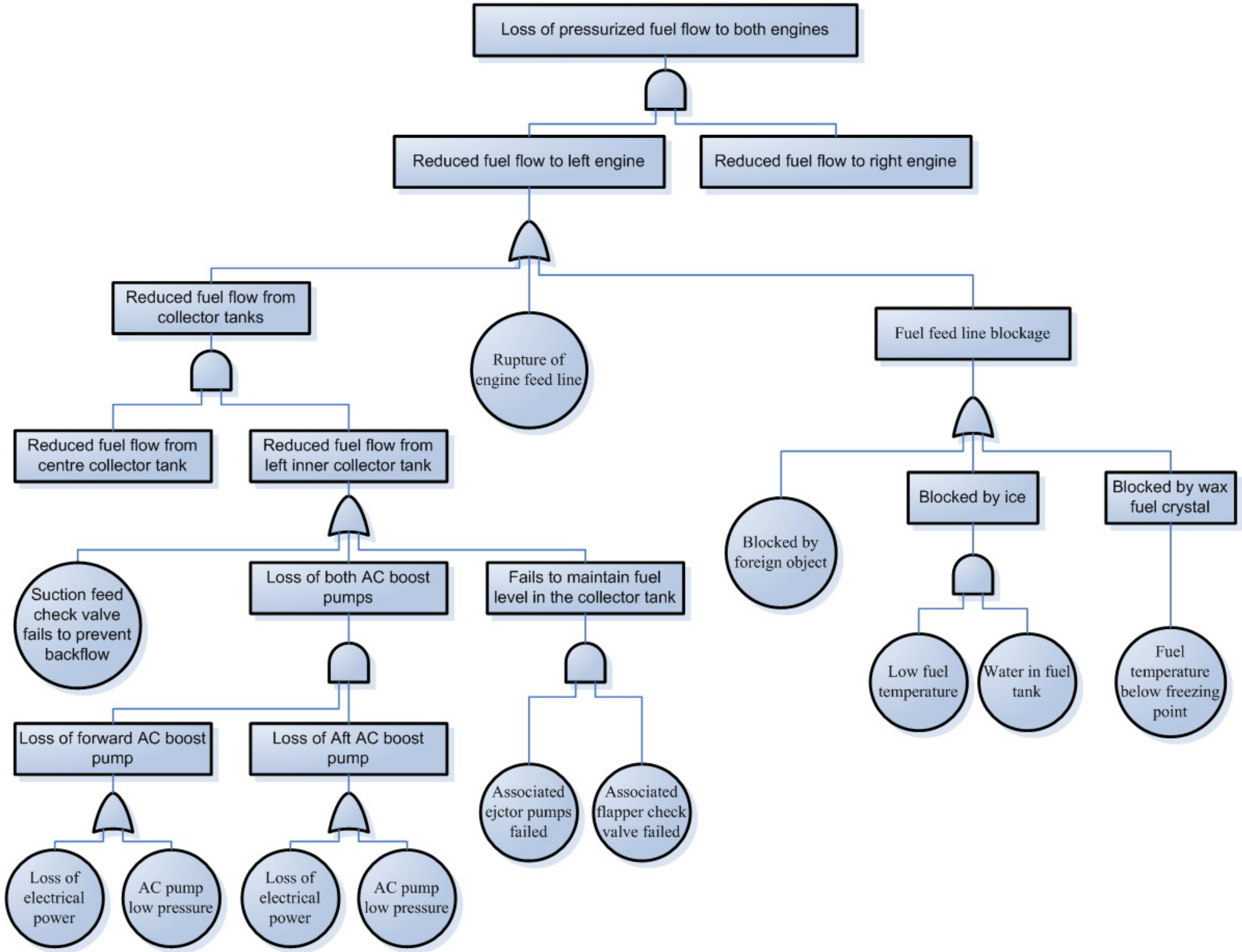


Figure 4-3 Loss of pressurized fuel flow to both engines

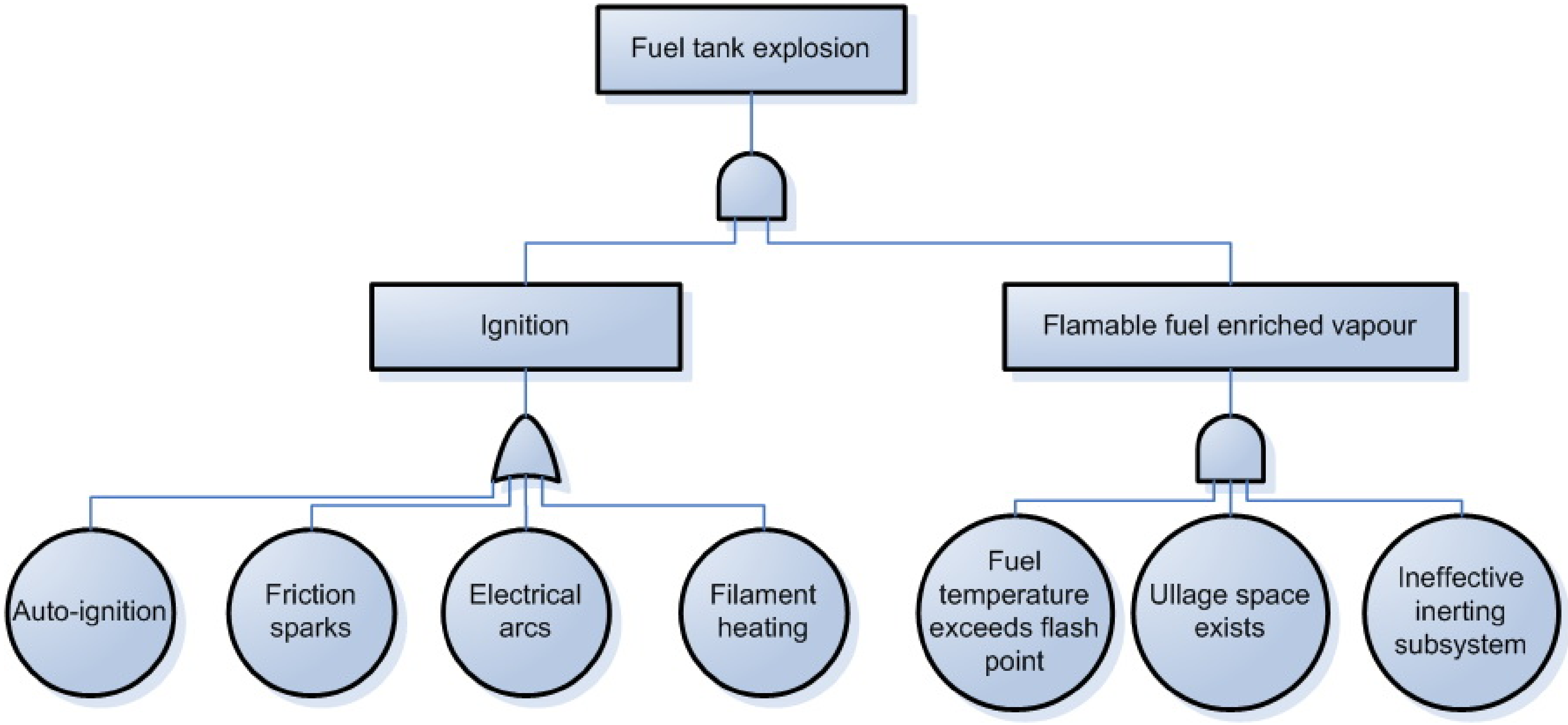


Figure 4-4 Fuel Tank Explosion

4.4 Conclusions

FHA analyses the functional hazard at the system level. On the contrary, FMEA determines the failure modes, effects and severity of each component. Based on the combination of FHA and FMEA, the key parameters and crucial components which have great impacts to the performance of fuel system can be identified. The detail information of required parameters and components are shown as the following tables.

Table 4-4 FHA and FMEA Results Summary

<table>
<tr><td colspan="3">Failure condition</td></tr>
<tr><td colspan="3">Loss of pressurized fuel flow to both engines</td></tr>
<tr><td>Severity</td><td>Related component</td><td>Failure detect method(s)</td></tr>
<tr><td>Catastrophic</td><td>AC boost pump</td><td>AC boost pump pressure switch
Engine FEDAC
Fuel temperature sensor and water detector</td></tr>
<tr><td>Parameters</td><td colspan="2">Fuel flow pressure and rate, electrical power signal, fuel temperature and water signal</td></tr>
<tr><td colspan="3">Failure condition</td></tr>
<tr><td colspan="3">Fuel tank explosion</td></tr>
<tr><td>Severity</td><td>Related component</td><td>Failure detect method(s)</td></tr>
<tr><td>Catastrophic</td><td>OBIGGS
Flame arrestor
Heat exchanger</td><td>Fuel temperature monitoring
Fuel pumps monitoring</td></tr>
<tr><td>Parameters</td><td colspan="2">Fuel temperature, oxygen ratio</td></tr>
</table>

Table 4-4 FHA and FMEA Results Summary (Cont.)

Failure condition		
Unable to shut off fuel feed flow to a nacelle in event of catching fire		
Severity	Related component	Failure detect method(s)
Catastrophic	Engine feed Shutoff Valve	FMC Engine FEDAC
Parameters	Valve status signal, fuel flow rate	
Failure condition		
Unable to shut off fuel feed flow to APU in event of catching fire		
Severity	Related component	Failure detect method(s)
Catastrophic	APU feed Shutoff Valve	FMC Engine FEDAC
Parameters	Valve status signal, fuel flow rate	

5 Fuel Temperature Study

5.1 Introduction

This chapter illustrates the motivation of the case study. According to the FTA results, there are two failure conditions of which the severity level are catastrophic, loss of pressurized fuel flow to both engines and fuel tank explosion, could be caused by one important parameter – the fuel temperature.

The fuel temperature has great impact on the flight safety. Low temperature will cause ice formation and wax crystals, which will block the fuel-feed inlets and reduce the pressure of fuel flow pressurized by the fuel pump due to the increase of viscosity respectively. High fuel temperature will increase the risk of fuel tank explosion caused by the fuel auto ignition or electric spark.

The table 5-1 below shows the typical characteristics of Jet A-1, which is the most typical and widely used jet fuel in the world except the USA, where Jet A is used.

Table 5-1 Typical JET A-1 Characteristics

	Jet A-1
Flash point	38℃
Auto-ignition temperature	210℃
Freezing point	-47℃ (-40℃ for Jet A)

5.2 Cold Fuel Hazards

During flight, the fuel temperature in the tanks decreases, due to the low temperature of outer atmosphere, especially for the long range civil aircraft. The decrease cause the water dissolves from the fuel and the separated water accumulates at the bottom of the tank, as it is denser than the fuel. The water will freeze when the fuel temperature drops below its freezing point and may block the fuel inlets. It is confirmed that the Boeing 777 accident (British Airways) at Heathrow airport was caused by the ice formation in the engine fuel feed inlet. The separated water also provides breeding ground for the bacteria which can cause the erosion of structure and components in the fuel tank. In order to solve the water accumulation, the scavenge jet pumps are used to mix the separated water within fuel, and then the mixed fuel will be feed to the engine for combustion.

Another hazard caused by the low fuel temperature is the wax crystals when the fuel is near the freezing point. Aircraft fuel is a complex mixture of different hydro-carbons that do not all solidify at the same temperature. When fuel is cooled, an increasing proportion of wax crystals form in the fuel as certain of the constituents begin to freeze. The wax crystals may block fuel feed lines and lead to the engine power fluctuations, power loss and even flame out since the insufficient fuel feed to the engine [20]. The figure 5-1 below shows the fuel temperature changes during a flight of B747, of which the maximum fuel capacity is about 180,000 kg. To solve this problem, the heat exchangers are usually used in the fuel tank, commonly installed in the collector fuel tank. These heat exchangers exchange heat between fuel and other aircraft systems which will be discussed later.

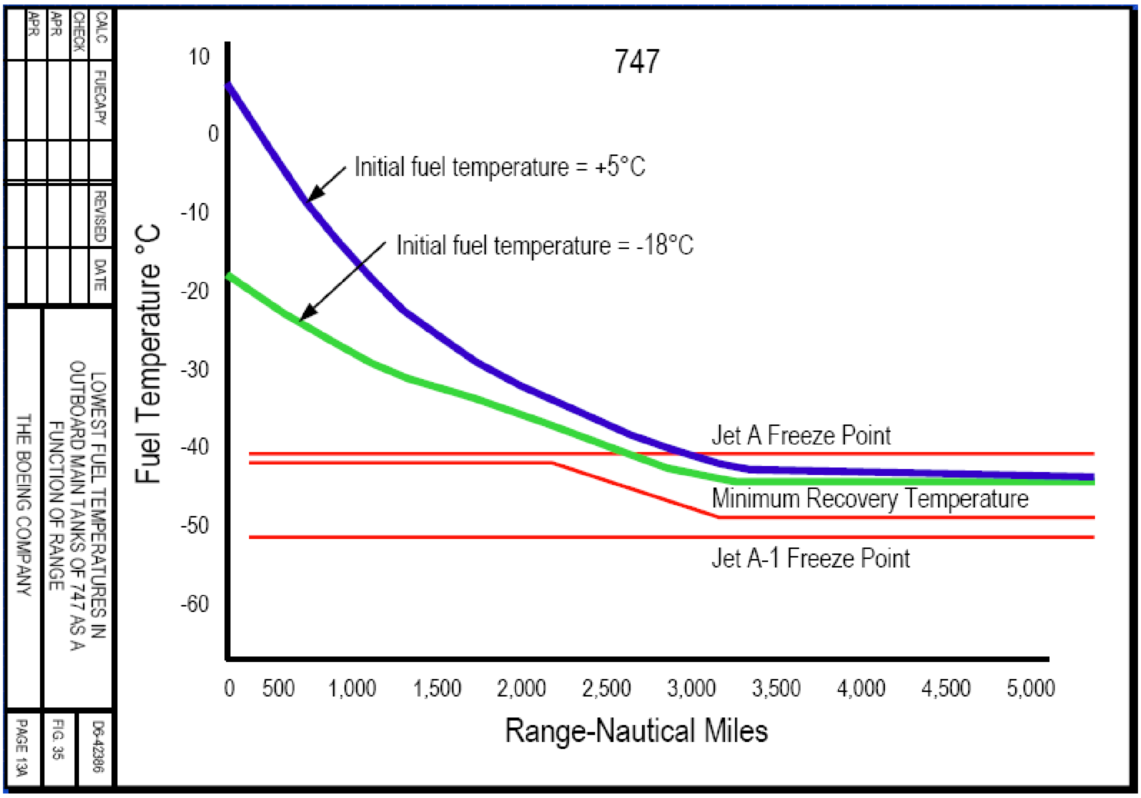


Figure 5-1 The Fuel Temperature Trends of B747 [21]

5.3 Hot Fuel Hazards

Since the TWA flight 800 accident in July 1996, there is great concern in the fuel tank explosion suppression of the civil airliners. After four years investigation, the National Transportation Safety Board (NTSB) concluded the result of accident is the explosion of flammable fuel/air vapours in the fuel tank [22].

Four primary factors can cause the ignition of fuel vapours within the aircraft fuel tank: electrical arcs, filament heating, friction sparks, and auto-ignition. The conditions which can ignite fuel/air vapours vary with pressures and temperatures within the fuel tank. The sloshing and spraying of fuel can also influence the condition. It is very difficult to predict the fuel tank flammability, therefore, the fuel air mixture in the aircraft fuel tanks is always considered as flammable vapour which ignition sources are restricted strictly [23].

In order to suppress the fuel tank explosion, the fuel tank inerting system was developed to protect the fuel tank. Normally the upper fuel tank space comprises fuel-enriched vapour of which oxygen ratio takes about 20%. This provides an explosive condition whilst a heat source or spark is occurred. The inerting system use nitrogen-enriched air to inert the fuel tank to eliminate the explosive condition by reduce the oxygen ratio to less than 12%. The nitrogen-enriched air is generated by the OBIGGS. Figure 5-2 shows the principles of typical fuel tank inerting system.

Although the inerting system can eliminate the threat of flammable vapour, the system cannot always work properly. There are also some cases the inerting system cannot maintains the low oxygen percentage in the fuel-enriched vapour such as the rapid descent of aircraft. To make sure the fuel temperature is in a relative low value during the mission is still a good solution.

The aircraft generates lots of heat, particularly from the hydraulic, environmental control system (ECS) and even the inerting system. For the supersonic aircraft, the aerodynamic heating plays an important role to the fuel tank. All the heat mentioned above needs to be absorbed by the fuel which can be used as heat sinks. This will cause the fuel temperature rise.

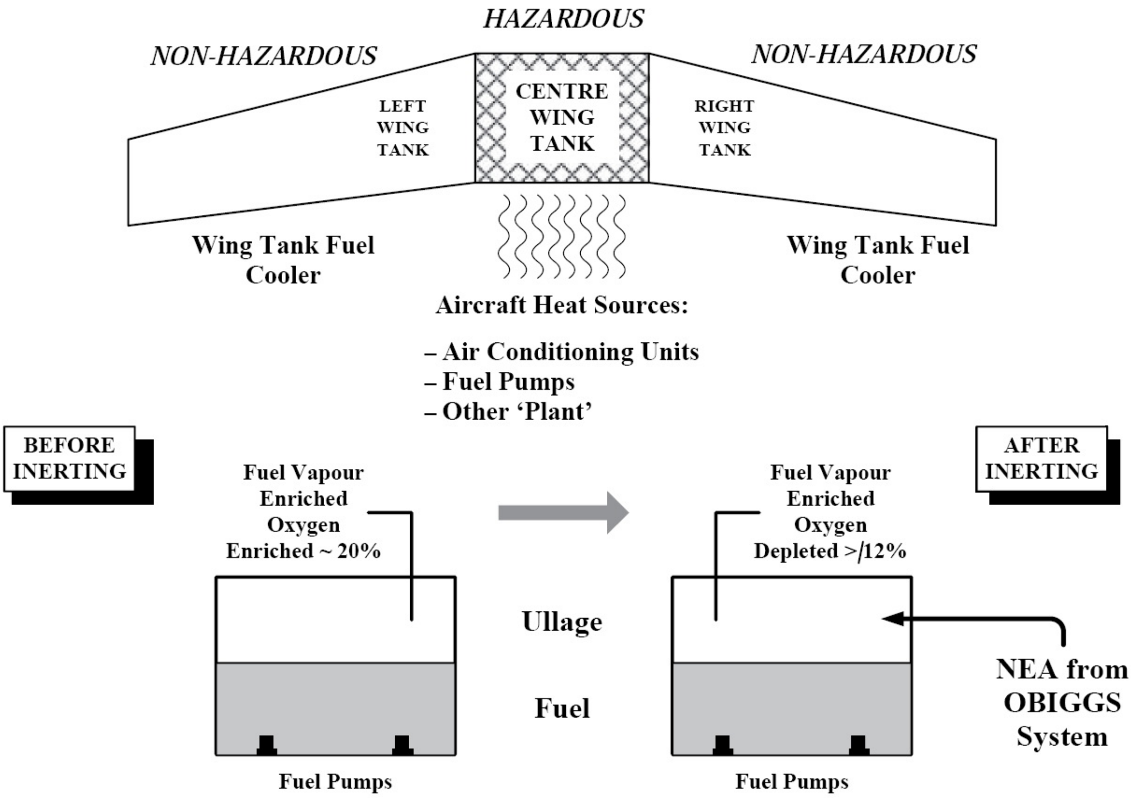


Figure 5-2 The Principles of Typical Fuel Tank Inerting System [20]

5.4 Conclusions

As stated above, both cold fuel and hot fuel are hazardous to the flight safety. Thus, to maintain the fuel temperature within a reasonable range is very important. For the modern large civil aircraft, the fuel capacity is very high. Once the temperature approached the danger point, several hours were needed to recover it. Therefore, the fuel temperature should be monitored and predicted strictly during flight. The fuel temperature is measured and monitored on the modern aircraft, once it reached the threshold point, an alert message will be displayed on the EICAS or ECAM. However, few aircraft employ the onboard fuel temperature prediction function.

In conclusion, the fuel temperature diagnosis and prognosis are essential to the fuel PHM system to increase the aircraft safety and reliability.

6 Fuel Temperature PHM Research

6.1 Introduction

This chapter is to develop an onboard fuel temperature PHM architecture which is suitable for the fuel system of FW-11. As stated earlier, rule-based expert system and model-based reasoning system are chosen to perform the diagnostic function. The prognostic function is achieved through Data-driven model-based approach.

6.2 Fuel Temperature PHM Architecture

The figure below illustrates the fuel temperature PHM architecture and its operating process of monitoring, diagnostics and prognostics. This PHM system provides three functions: monitoring, prognosis and diagnosis.

The first function is to monitor the fuel temperature in each tank and associated parameters such as the status of AC boost pumps and valves, fuel quantity data in each tank, fuel consumption rate to the engine and the outer temperature. If the fuel temperature approached the danger point, an alert message of “low fuel temperature” or “high fuel temperature” will be displayed in the EICAS.

Based on the initial fuel temperature in each tank and operating status of associated components provided by the monitoring function, the expected fuel temperature in each tank can be calculated by the fuel temperature prediction model. The nominal performance data of these associated components are stored in this model to support the calculation of fuel temperature expectation. These data can be obtained from either calculation or experiments.

A comparison will be conducted between the actual fuel temperature and the expectation. If the disagreement of these two parameters exceeded the predefined range, an analysis process will be conducted to find and determine the reason for this discrepancy. This discrepancy can be considered as the trigger of the analysis process. It also can be used as the criterion of failure determination while combining with other parameters.

The prognostic function is used to forecast the fuel temperature trends in each fuel tank, especially the temperature trends in the collector tanks. By using the data from monitoring function, the occurrence time of the fuel temperature reaching the dangerous point can be predicted. This forecast will be displayed in the EICAS as a caution message to advise the pilot to fly lower or faster if necessary.

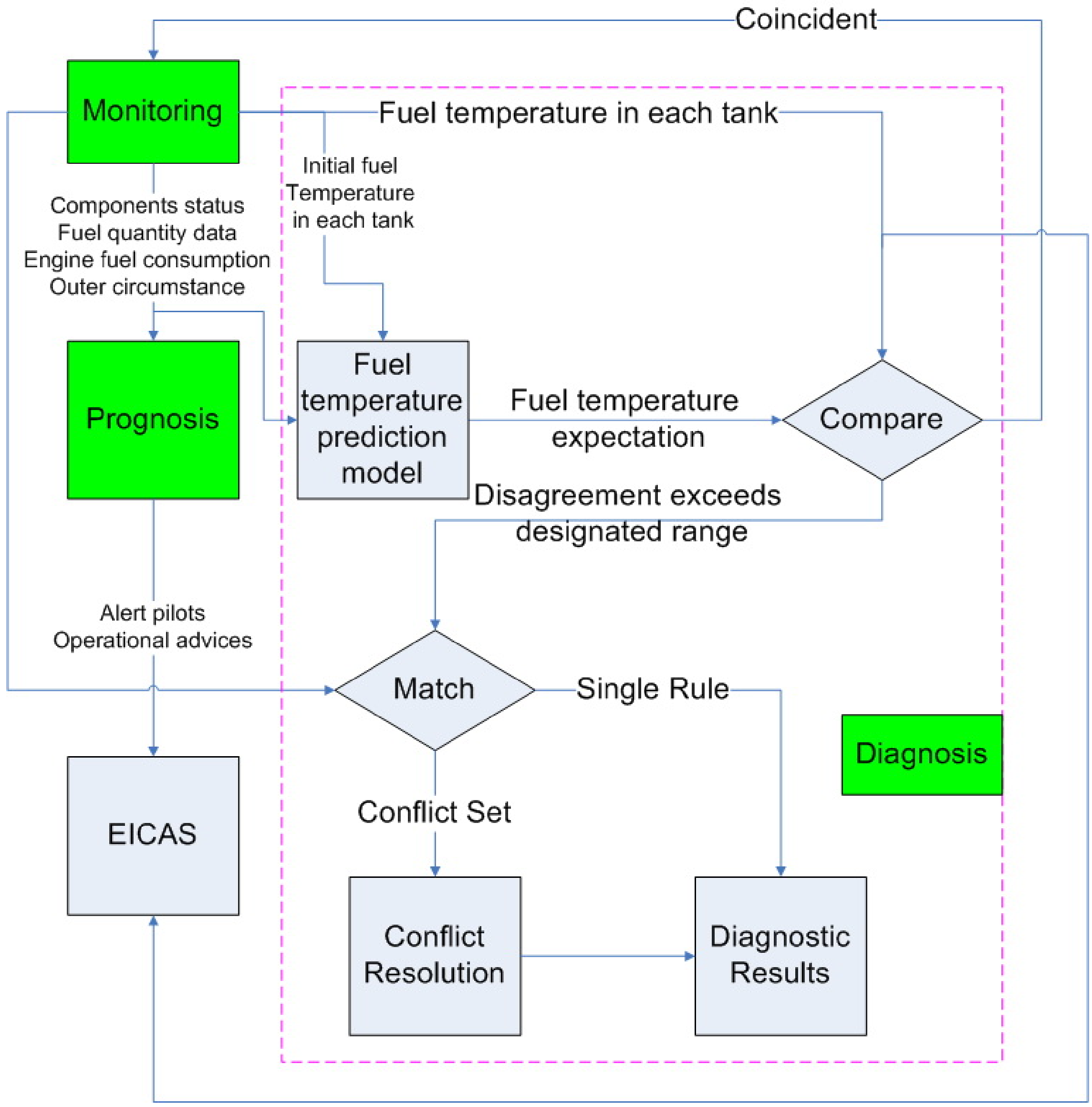


Figure 6-1 Fuel Temperature PHM Architecture

6.3 Fuel Temperature Monitoring Research

The fuel temperature monitoring function is mainly used to monitor the fuel temperature in each tank. A fuel temperature sensor is installed in each fuel tank to gauge the temperature and transfer the signal to the FMC. Once the fuel temperature approached the danger point, an alert message of “low fuel temperature” or “high fuel temperature” will be displayed in the EICAS to alert the pilots.

This function also monitors the relevant components status and parameters for the diagnosis and prognosis functions. The fuel quantity in each fuel tank is measured and monitored by a set of fuel quantity probes and fuel densitometers located in the fuel tanks. The fuel consumption rate to both engines is also acquired by the monitoring function.

The operating condition of AC boost pumps are monitored by the pressure switch mounted in the outlet of each fuel pump. The monitoring function also monitors the working status of shutoff valves in the fuel feed lines and fuel transfer lines. These components operating status are sent to the FMC for the following functions. There are water detectors at the fuel tanks sump area to detect water contamination.

There is a fuel temperature detector emerged in the lower wing structure of aircraft to monitor the temperature of outer atmosphere. This temperature has taken the aerodynamic heating of the lower wing surface and solar heating reflection when the aircraft is on the ground into consideration. Similarly, there is a fuel temperature detector emerged in the upper wing structure of aircraft to monitor the temperature of upper wing skin. This temperature has taken the aerodynamic heating of the upper wing surface and solar heating into consideration. The temperature of upper and lower wing skin can be obtained from these two detectors by multiply an experimental coefficient.

The temperature of the working fluid in the heat exchanger is also monitored by this function. This parameter gives alert message to the ECIAS and provides data to the fuel temperature prediction model in the FMC.

6.4 Fuel Temperature Diagnosis Research

This section is to discuss the fuel temperature associated diagnostic function in which rule-based expert system and model-based reasoning system are implemented.

6.4.1 Rule-based Expert System

The rule-based expert system is a fast and reliable diagnostic method which widely used for failure detection and diagnostic decision making. This system mainly utilizes “if-then-else” principle to describe the rule statements. These rule statements are the primary contents related to domain knowledge. Generally, this expert system comprises five primary functional blocks which are knowledge base, reasoning engine, data base, explanatory interface and knowledge acquisition [19]. The relationships between these five functional blocks are shown in the figure below.

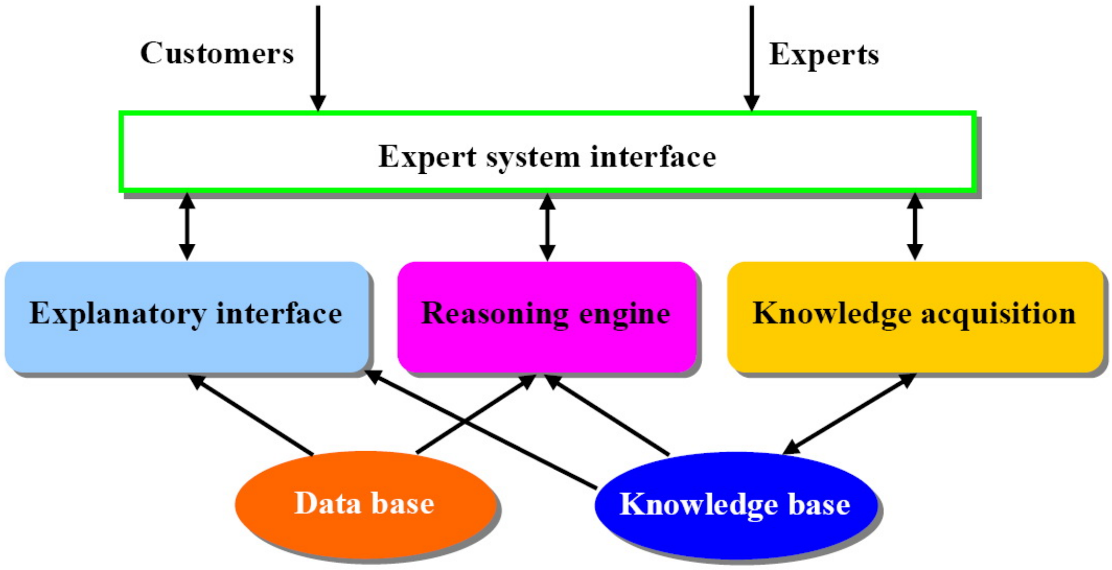


Figure 6-2 Rule-based Expert System Schematic Diagram [19]

The knowledge base is mainly used to store and manage the relevant domain expert knowledge. Data base is a special place for expert system to store the current system operational data which include the real-time system operating status, the inputs from customers and interim results of inferring process.

The explanatory interface is to provide description of any problems from customers. Reasoning engine contains a set of computer programme to determine the selection of the related knowledge from knowledge base and infer the evidences from customers to provide the final decision for the specific problems. The knowledge acquisition is used to transform the engineering experts' knowledge into computer programme to establish the knowledge base.

The core of rule-based expert system is domain expert knowledge which is the foundation of diagnostic decision making. Typically, this domain expert knowledge can be obtained from system operational principle, operational experiences, and FTA. FTA has become a very important analysis tool for providing the source of domain expert knowledge. The FTA results of unexpected fuel temperature changes in collector tank are shown in the figures below.

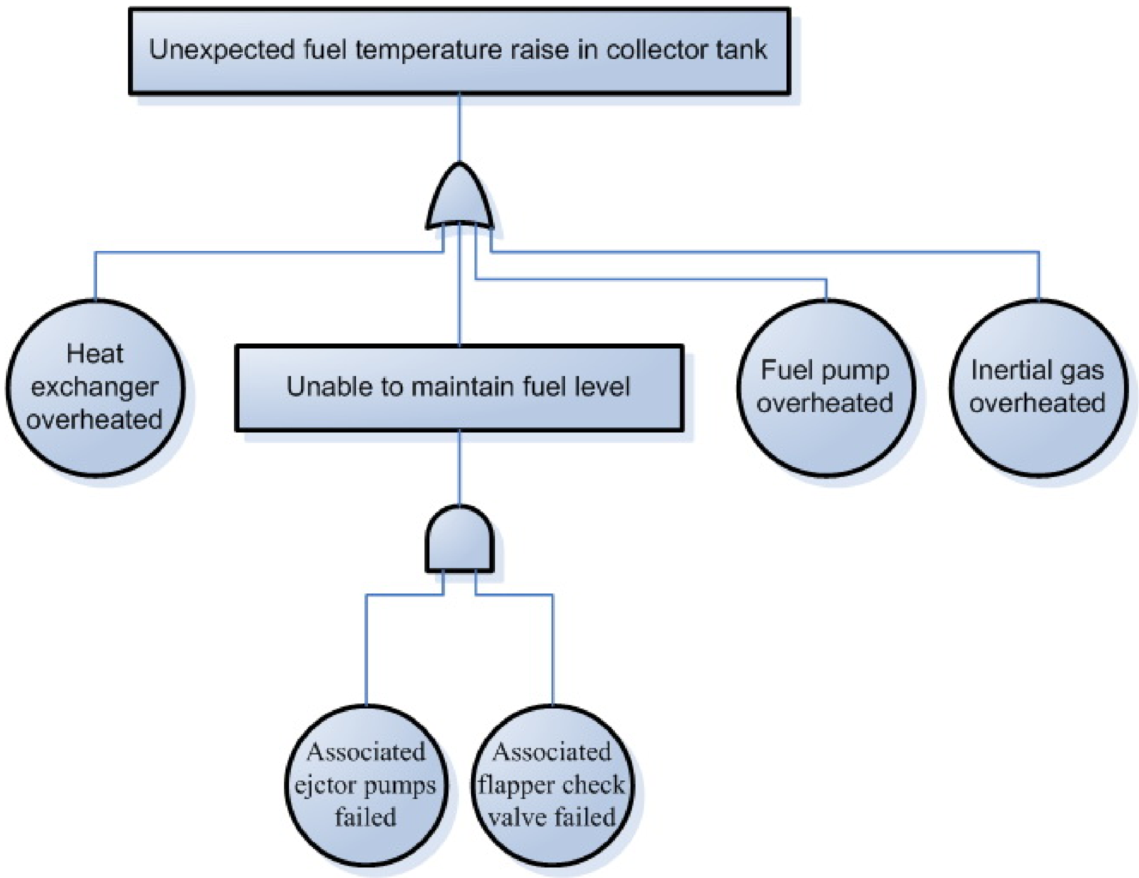


Figure 6-3 Unexpected Fuel Temperature Raise in Collector Tank

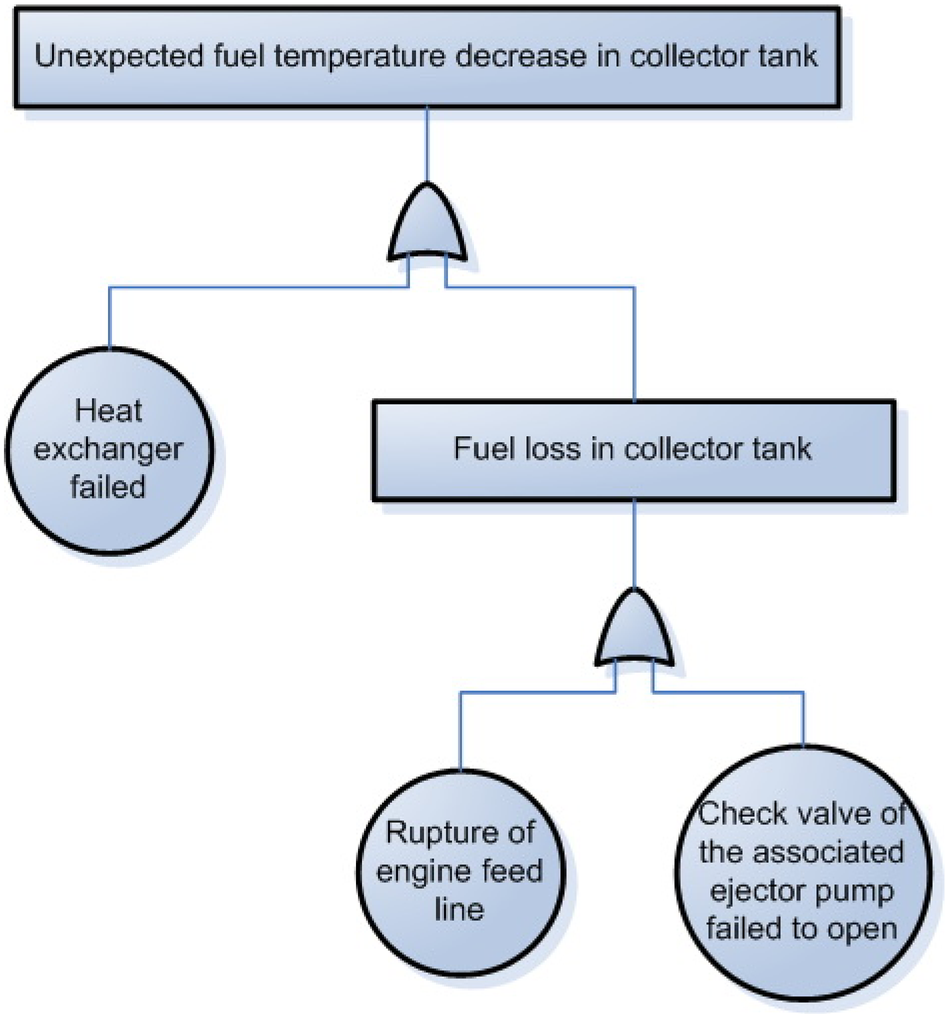


Figure 6-4 Unexpected Fuel Temperature Decrease in Collector Tank

6.4.2 Model-based Reasoning System

In the fuel system of FW-11, the mechanical components associated with the fuel temperature include suction feed inlet screens, suction feed check valves, scavenge ejector pumps, engine feed check valves and flapper check valves. The status of these components cannot be monitored by the FMC. For the mechanical components which have no sensed data, the model-based reasoning system is a good choice for the diagnostic technique. The working process of this diagnostic technique is shown in figure 6-5.

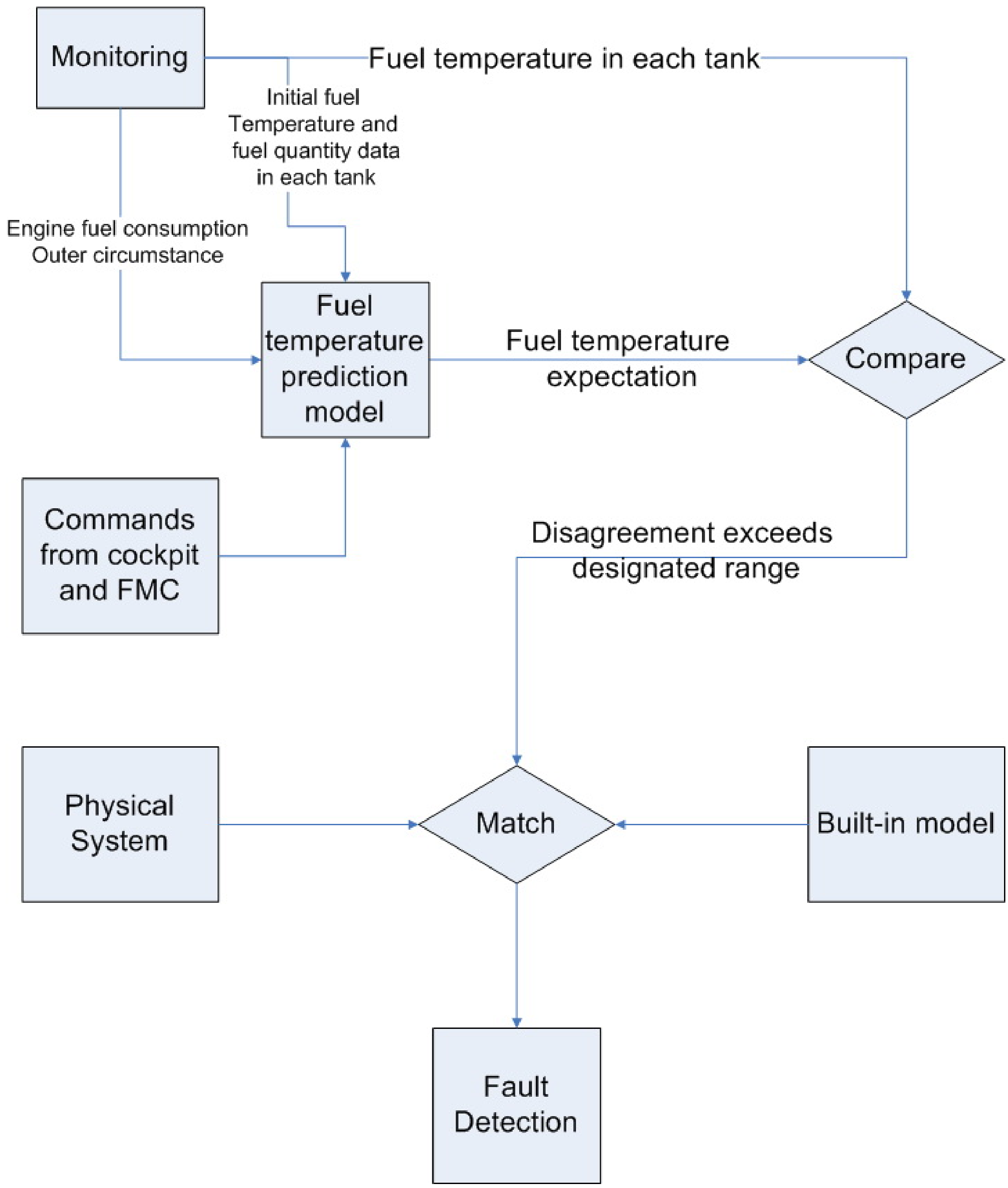


Figure 6-5 Working Process of Fuel Temperature Diagnosis

In the first step, the fuel temperature prediction model calculates the expected fuel temperature based on the inputs which include the initial fuel temperature and fuel quantity in each fuel tank, operating commands from the cockpit and FMC, real-time engine fuel consumption rate and temperature in the lower structure provided by the monitoring function. This fuel temperature prediction model works in the same inputs as the real condition to provide the nominal output. This model assumes all the relevant components are working in the normal condition or responding the commands correctly.

In the second step, a comparison between the nominal fuel temperature and the real data is conducted. If these two parameters are discrepant, it will trigger the failure detection process.

Finally, the physical system matches the built-in model to determine the cause of this discrepancy or identify the locations of failed mechanical components.

6.5 Fuel Temperature Prognosis Research

As mentioned in the literature review, Boeing and Airbus have developed programme to forecast the fuel temperature trends in each fuel tank during the mission. However, this software cannot provide the real-time temperature prediction. It can only predict the fuel temperature changes in the normal operation. Another drawback of this software is that it relies on the weather forecast, which will influence the accuracy of prediction result. Therefore, the onboard fuel temperature prognostic system is necessary.

In this section, an onboard fuel temperature prognostic architecture will be established to forecast the remaining time for the hazard fuel temperature approaching. The data-driven model-based approach is used to achieve this target.

6.5.1 Fuel Temperature Prediction Model

For a fixed aircraft fuel system, the rate at which the fuel temperature changes is a function of air temperature, heat from heat exchangers, specific heat capacity, the inlet fuel flow rate, the outlet fuel flow rate, the inlet fuel temperature, the fuel mass within the fuel tank, the fuel temperature in the fuel tank and time. Figure 6-6 shows the heat transfer mechanism of a typical fuel tank.

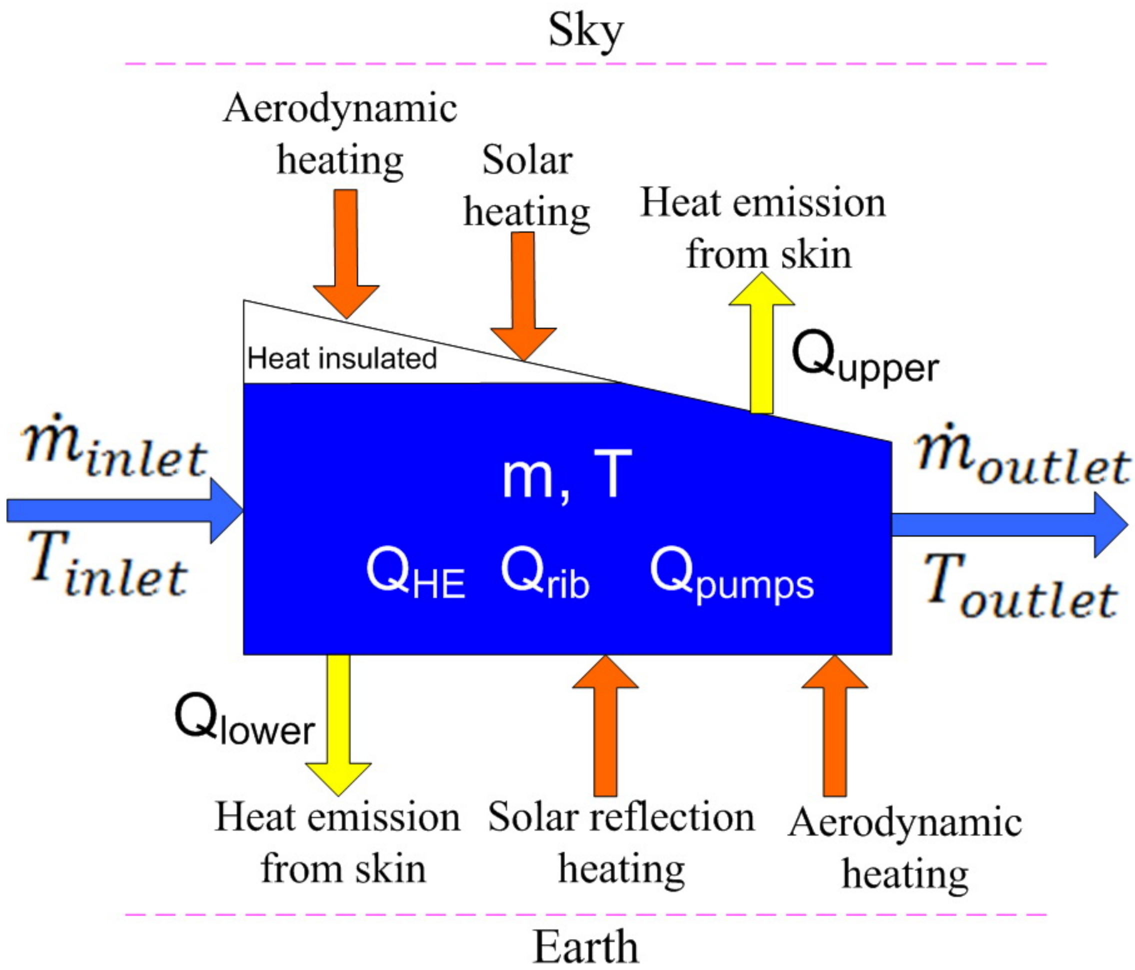


Figure 6-6 Heat Transfer Mechanism

The fuel tank can be considered as an open system undergoing a nonsteady-flow process. The fuel/air vapour in the upper space is assumed to be heat insulated. Another assumption is the fuel enter into the fuel tank can be mixed with the original fuel equally instantly, all the fuel in the fuel tank is in the same temperature T. According to the thermodynamic theory, the change of internal energy (dU) in the fuel tank can be expressed as equation 6-1.

$$dU = dU_{inlet} - dU_{outlet} + \delta Q - \delta W \tag{6-1}$$

Where dU_{inlet} is the internal energy enters into the fuel tank; dU_{outlet} is the internal energy leaves the fuel tank; δQ is the heat exchange between fuel and surrounding structures or components. It contains the following heat source: heating from the heat exchanger Q_{HE} , aerodynamic heating to the upper and lower wing skin, heat emission from the lower skin Q_{lower}, heat emission from the upper skin Q_{upper}, heat exchange with the ribs and spars surrounding the fuel Q_{rib} , solar heating and solar reflection heating when the aircraft is on the ground; δW is the output work of the fuel tank.

Assuming the kinetic energy of the fuel flow will not convert to heat, all the fuel tanks of the aircraft are in the same fuel level, it means that the kinetic and potential energy is ignored. Then the following equation can be gotten:

$$\frac{dU}{dt} = \delta Q + c_p \cdot \dot{m}_{inlet} \cdot T_{inlet} - c_p \cdot \dot{m}_{outlet} \cdot T_{outlet} \quad \textbf{(6-2)}$$

Where c_p is the specific heat capacity which varies with the fuel temperature; $\dot{m}_{inlet}$ and $\dot{m}_{outlet}$ is the fuel flow rate enter or leave the fuel tank respectively; T_{inlet} and T_{outlet} is the temperature of fuel enter or leave the fuel tank respectively.

From the definition of specific heat capacity, the formula below can be gotten:

$$\frac{dU}{dt} = \frac{d(c_p mT)}{dt} = c_p m \frac{dT}{dt} + c_p T \frac{dm}{dt} \quad \textbf{(6-3)}$$

$$\frac{dU}{dt} = c_p m \frac{dT}{dt} + c_p T(\dot{m}_{inlet} - \dot{m}_{outlet}) \quad \textbf{(6-4)}$$

Combine the equation 6-2 and 6-4, and let $T_{outlet} = T$, then:

$$\frac{dT}{dt} = \frac{\delta Q + c_p \dot{m}_{inlet}(T_{inlet} - T)}{c_p m} \quad \textbf{(6-5)}$$

Or

$$T_{i+1} = \frac{\delta Q + c_p \dot{m}_{inlet}(T_{inlet} - T_i)}{c_p m_i} \Delta t + T_i \quad \textbf{(6-6)}$$

Based on the equation 6-5 or 6-6, a fuel temperature prediction model can be constructed. A prediction model constructed in the Simulink is shown as an example in the figure below.

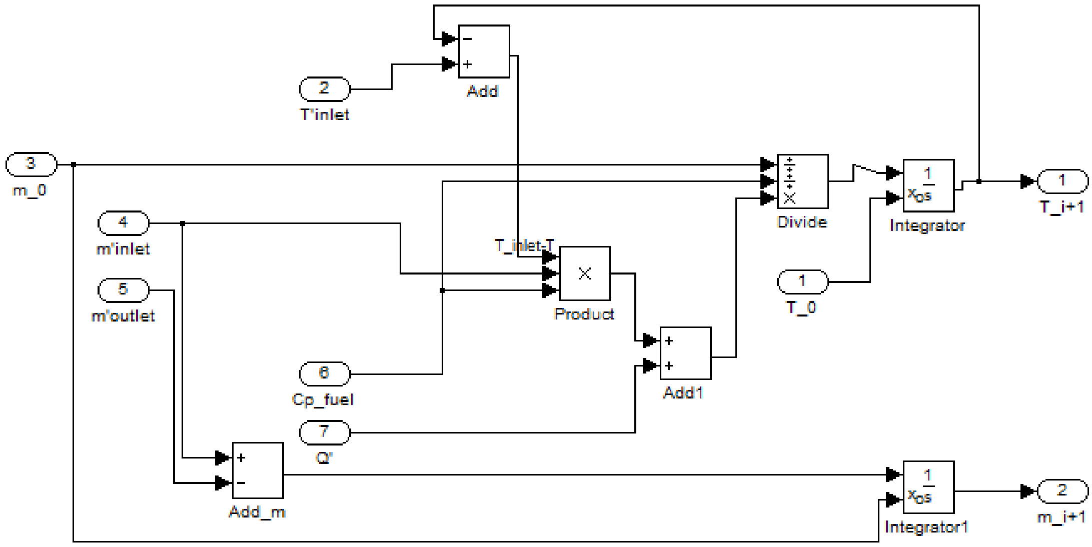


Figure 6-7 Fuel Temperature Prediction Model based on Simulink

6.5.2 Fuel Temperature Prognostic Architecture

The fuel temperature prognosis predicts the occurrence time of the dangerous fuel temperature approaching. The working process of this fuel temperature prognostic technique is shown in figure 6-8.

First, the fuel temperature prediction model receives the current temperature in each fuel tank as the initial parameter from the monitoring function. The associated components status, fuel quantity data in each tank, engine fuel consumption rate and temperature in the lower and upper wing skin are also transmitted to the prediction model.

Based on this data, an integrating process will be conducted to determine the occurrence time of dangerous fuel temperature for the following comparison to the remaining mission time. A caution message will be sent to the EICAS to alert the pilots if the occurrence time is less than the remaining mission time.

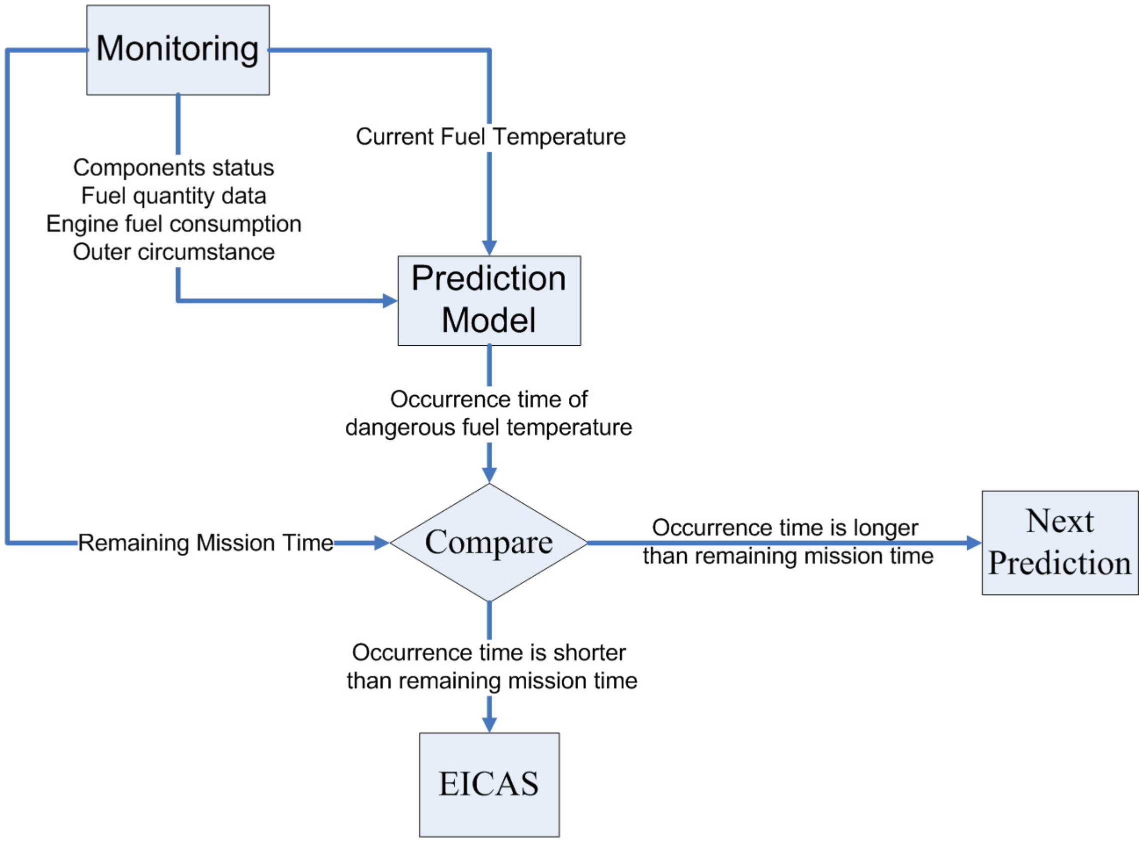


Figure 6-8 Fuel Temperature Prognosis

6.6 Conclusions

In this chapter, the fuel temperature PHM architecture was established for the fuel system to perform the monitoring, diagnosis and prognosis functions so as to increase the safety and reliability of FW-11.

7 Conclusions and Future Work

7.1 Conclusions

The target of this thesis was to implement the PHM technology to the fuel system of FW-11 to make sure the successful civil aviation market. The FW-11 is the group design project which the author participated. The detail information of the GDP is shown in Appendix A.

PHM system on board the aircraft enables the real-time transformation of system status data into alert and maintenance information during all ground or flight operating phases, which can support pilots and ground maintenance crew making decision. The fuel system PHM will increase the competitive capability of FW-11.

The research started with the literature review which illustrated the roadmap, current application and the challenges of PHM system. It also introduced the primary functions and the technologies of PHM system. The fuel temperature prediction development was also included in this review.

After the literature review, an assumed fuel system of FW-11 was established firstly according to the conceptual design results. This assumed fuel system met the airworthiness regulation requirements such as FAA, EASA and CAAC. All research efforts in this thesis were based on this assumed fuel system architecture. This fuel system stores enough fuel required by the mission and to supply fuel to the engine and APU at proper rate, pressure and temperature under any operating conditions safely and continuously. This fuel system controls the fuel consumption order to maintain the CG of aircraft as forward as possible since the weak static stability. The inerting subsystem was deployed in this fuel system to reduce the risks of fuel tank explosion. There are heat exchangers installed in the fuel collector tanks to sink the heat from inerting subsystem and hydraulic system.

In order to identify all failure conditions which the system may cause, a FHA was conducted for the fuel system of FW-11. The FHA provided a starting point for the following more in-depth FMEA and FTA. The FHA and FMEA results showed that the failure of fuel feed subsystem, fuel storage subsystem are more serious than other subsystems. Based on these results, FTA was conducted to find the probable causes of four catastrophic failure conditions.

According to the FTA results, the fuel temperature was selected as the case study of this thesis. The hazards of cold fuel and hot fuel were investigated to illustrate the essentiality of fuel temperature diagnosis and prognosis.

Finally, the fuel temperature PHM architecture was established for the fuel system PHM technology development. The rule-based expert system and model-based reasoning system are chosen to perform the diagnostic function. In order to obtain the domain expert knowledge, the FTA of unexpected fuel temperature changes in the collector tanks was conducted. For the prognostic function, it is achieved through Data-driven model-based approach. A proposal fuel temperature prediction method was also derived from the thermodynamic analysis of the typical fuel tank.

To sum up, the above research works provided a new concept for the fuel system PHM development. Based on the FHA, FMEA and FTA results, the fuel temperature was chosen to perform the PHM functions which include monitoring/detection, diagnostics and prognostics. A comprehensive PHM architecture of fuel temperature was established. This architecture will increase the aircraft safety and reliability dramatically. The research objectives of this thesis were fully achieved.

7.2 Future Work

As stated earlier, the PHM system covers lots of complex concepts, tools, approaches, techniques and technologies. This thesis was only to stand at the system level to implement the real-time monitoring, diagnostics and prognostics of fuel temperature. In order to meet the entire research objectives of the aircraft fuel system PHM, the research work should be extended to a broader range instead of only focusing on one component, parameter, or subsystem.

More inside failure modes of components and relevant parameters should be investigated to enhance the monitoring capability. For the fuel temperature diagnostic function, more in-depth FTA should be conducted to increase the accuracy of failure diagnosis. As for the fuel temperature prognostics, more accurate fuel temperature prediction model needs to be developed before the practical implement of PHM system.

Since the insufficient components and system data for the quantitative analysis in the conceptual design stage, this thesis only focused on the qualitative prognostic research. An accurate simulation of the temperature prediction model needs to be conducted to verify this model in the detail design stage.

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APPENDICES

Appendix A Group Design Project

A.1 Introduction

A.1.1 Background

This part gives a brief description of the background of Group Design Project (GDP) the author took part in. The GDP title is Flying Wing Civil Airliner, and the abbreviation is FW-11.

FW-11 is a three-year collaborative civil aircraft project between AVIC and Cranfield University. The major target of this project is to develop a novel and unique commercial flying wing aircraft of which seating capacity is from 150 to 250 proposed by AVIC.

FW-11 is an innovative 250-seat long range airliner, which is aimed at international civil aviation market, focusing on Asia-Pacific Region, Europe and North American primarily. The primary competitor for FW-11 is B787-8, in order to win the competition, the FW-11 need to achieve the following targets: more comfortable, lower life cycle cost and environmental friendly compared with B787-8 and existing civil airliners. Benefited from the aerodynamics of flying wing configuration, FW-11 has great advantages on the fuel efficiency since the drag during cruise is much smaller than the conventional aircraft.

The whole design process of FW-11 was divided into three stages: conceptual design, preliminary design and detail design. From 2011 to 2013, about 20 delegates from AVIC will be involved each year to participate in each stage. The year, 2011, is the first year of FW-11 project and 23 delegates and a tutor from AVIC were in the project. The conceptual design lasts about six months from April to September.

In the conceptual design stage, the target market was identified, and then a set of key parameters such as size and range were determined, finally, the configuration of FW-11 was decided. All the results above will be organized in the aircraft specification and delivered to the next stage as the top level design inputs.

A.1.2 Design Process

The conceptual design process was divided into three phase:

1. Phase Ⅰ: Derivation of Requirements.
2. Phase Ⅱ: To design a conventional aircraft as baseline.
3. Phase Ⅲ: To design the FW-11 and comparing with baseline aircraft.

A.1.2.1 Phase Ⅰ

During Phase Ⅰ, in order to get the design requirements of the FW-11 for the next two phases, the members were divided into six teams: Market, Manufacturer and Operator Data and Model, Aerodynamic, Geometry, Performance. A comprehensive survey of current civil aviation industry was carried on. A data base was built by collecting data from Airbus and Boeing, and then various methods were employed to check the validation of the data, the involved aircrafts include B737, B757, B767, B777, B787, A320, A321, A340 and A330. In this phase, the author was in charge of the market analysis and derived the requirements of FW-11 which will be discussed in the market analysis part.

A.1.2.2 Phase Ⅱ

In the second phase, the members were allocated into six teams which include Geometry, Aerodynamic, Engine Sizing, Cabin layout, Mass and Landing Gear, Performance. Based on the requirements derived from the first phase, a conventional aircraft was designed as a baseline aircraft. The author was in the performance team, and primarily in charge of the cruising performance calculation.

A.1.2.3 Phase Ⅲ

During the third phase, seven teams worked together to accomplish the design of FW-11. Besides the six teams in the Phase Ⅱ, the structure team was assigned to enable further development of conceptual design. The design process of FW-11 is shown as Figure A-1.

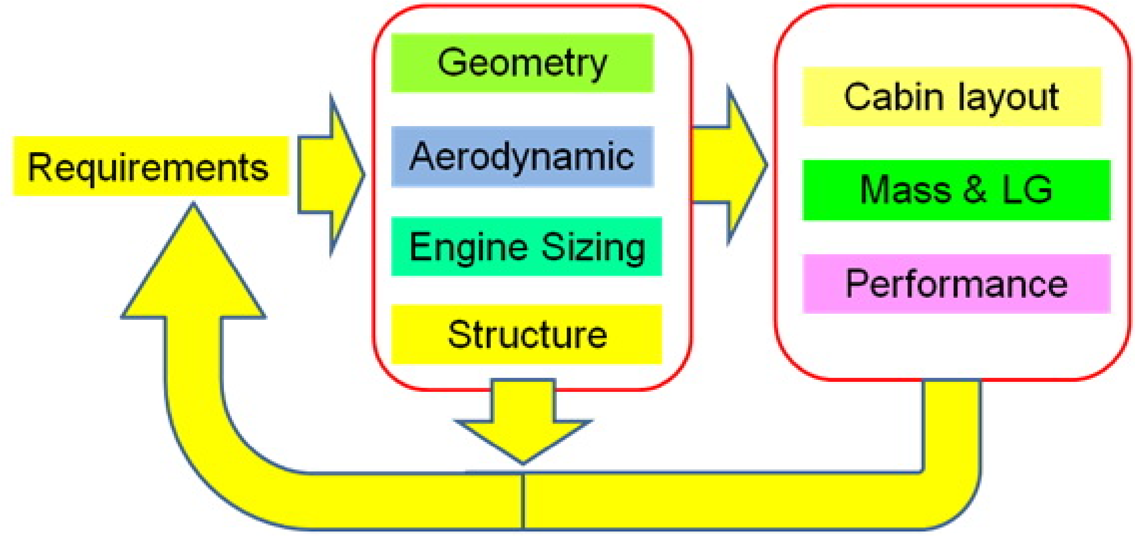

Figure A-1 Design Process of FW-11 in Phase Ⅲ

A.2 Market Analysis

At the beginning of the Flying Wing design process, the inputs for the design should be customer needs. The requirements and design drivers for FW-11 can be identified from the market analysis.

The market analysis includes market outlook, target market, customer requirements investigation, family issues, and of course, entry service time.

A.2.1 Market Outlook

The air traffic growth relies on several factors including economic growth, fuel price changes, airline productivity gains, environmental issues and airports.

A.2.1.1 World Economy Trends

Recently revised data shows that in 2009 the World gross domestic product (GDP) contracted 1.9%. The world economy experienced the steepest global recession since the Great Depression. However, the global economy rebounded in 2010, with estimated growth rate 3.9% [26]. Figure A-2 shows the economic growth from 2000 to 2010 in term of GDP.

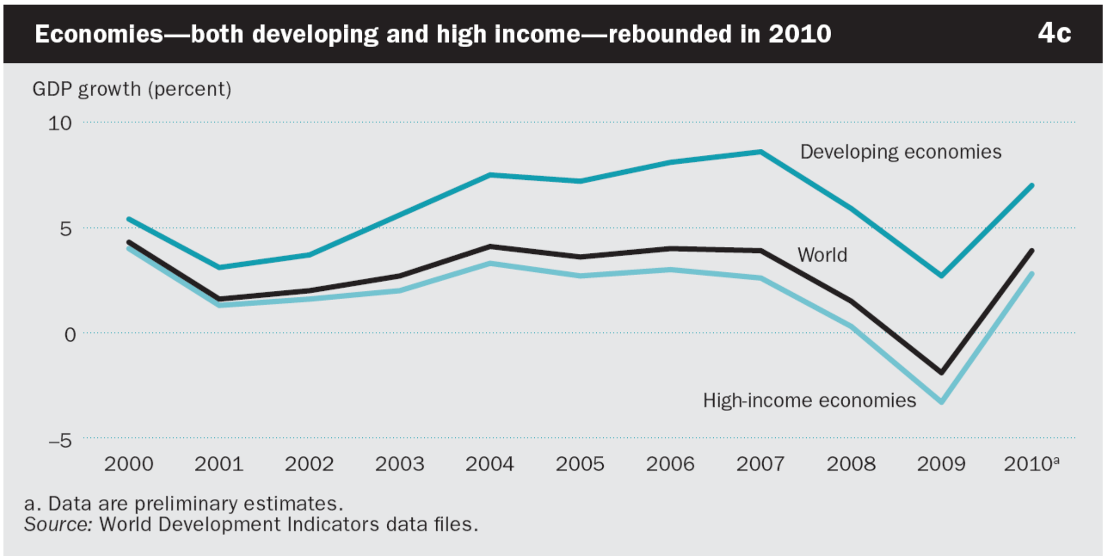

Figure A-2 Development in World GDP 2000-2010 [26]

According to the forecast by Boeing Company, the prediction of world economy growth rate is 3.2% from 2009 to 2029 annually, shown as Figure A-3.

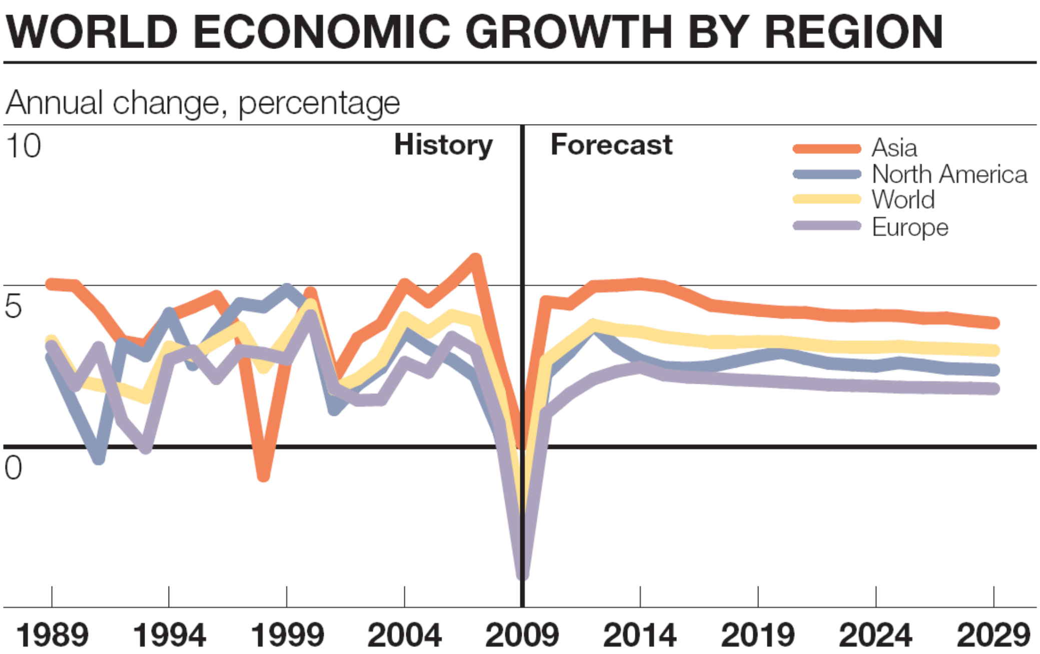

Figure A-3 World Economic Growth [27]

A.2.1.2 World Air Traffic Trends

According to the International Civil Aviation Organization (ICAO), the world air traffic is expected to grow at 4% annually in term of Revenue passenger kilometres (RPK), shown as Figure A-4.

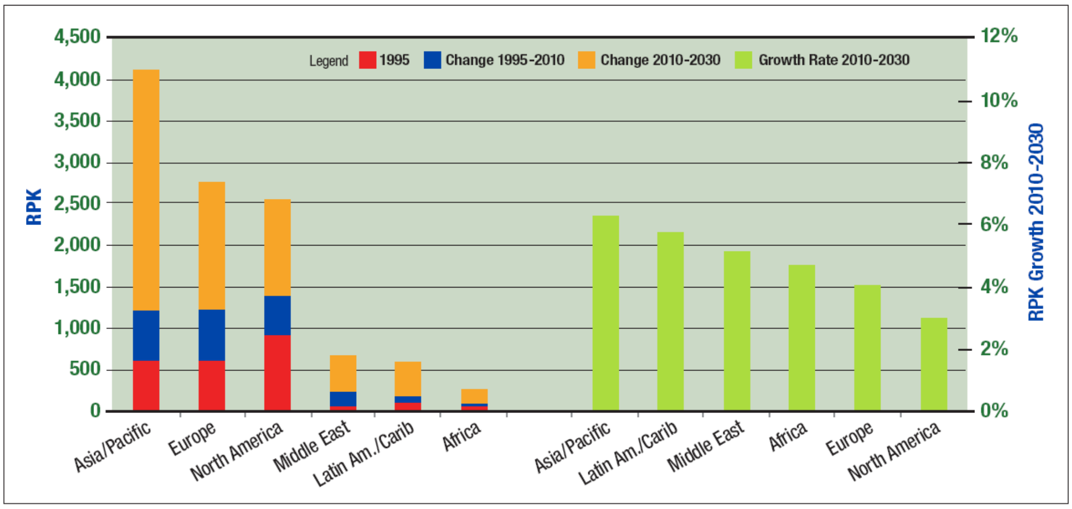

Figure A-4 ICAO Passenger Traffic Forecasts [28]

A.2.1.3 Industry Outlook

Airbus Outlook

Airbus predicts in its Global Market Forecast 2010-2029 that during the period from 2010 to 2029, global passenger traffic is expected to increase by 4.8% annually, shown as Figure A-5 [29]. In this report, Airbus also predicts that the Asia-Pacific airlines will lead world traffic by 2029, shown as Figure A-6 [29].

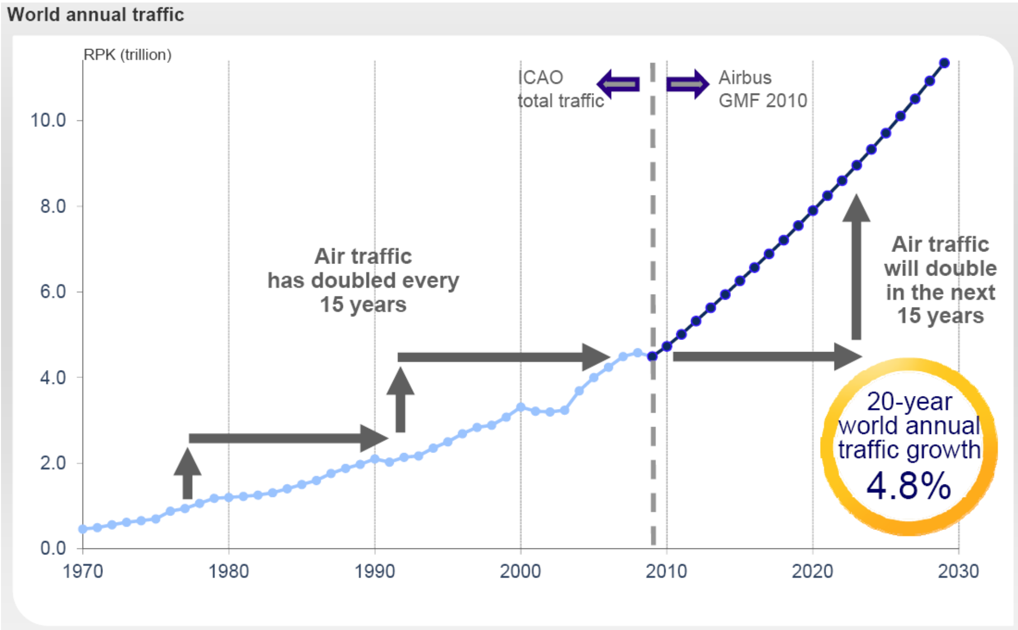

Figure A-5 World Annual Traffic Forecast [29]

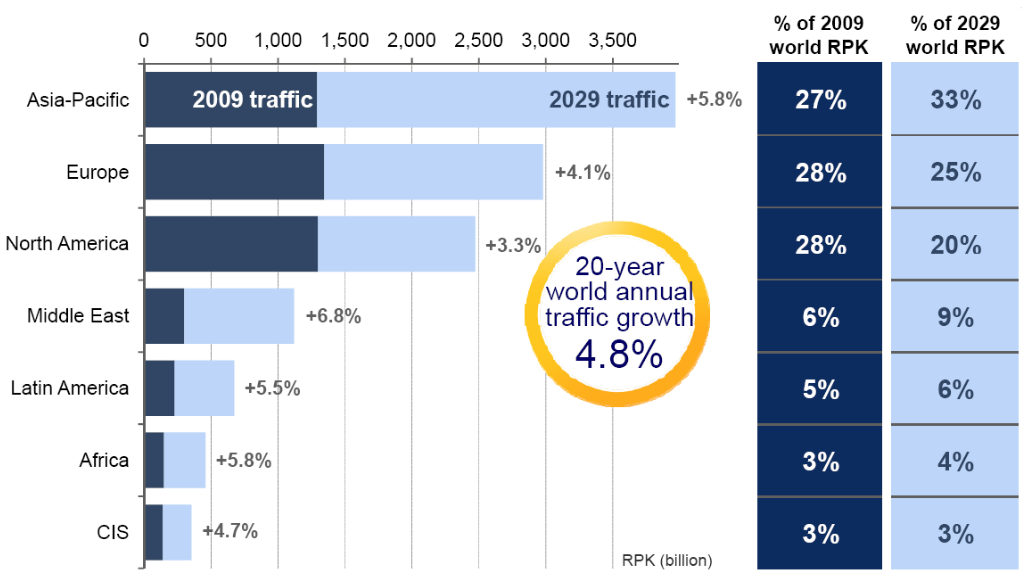

Figure A-6 2009 and 2029 Traffic Volume per Airline Domicile Region [29]

It is predicted that 25,800 new aircraft will be delivered to airlines and the market value will be $3.2 trillion. Among the new aircrafts, 17,870 aircrafts are single-aisle, however, twin-aisle aircrafts share 42% value, which is the largest portion of the new aircrafts shown as Figure A-7 [29].

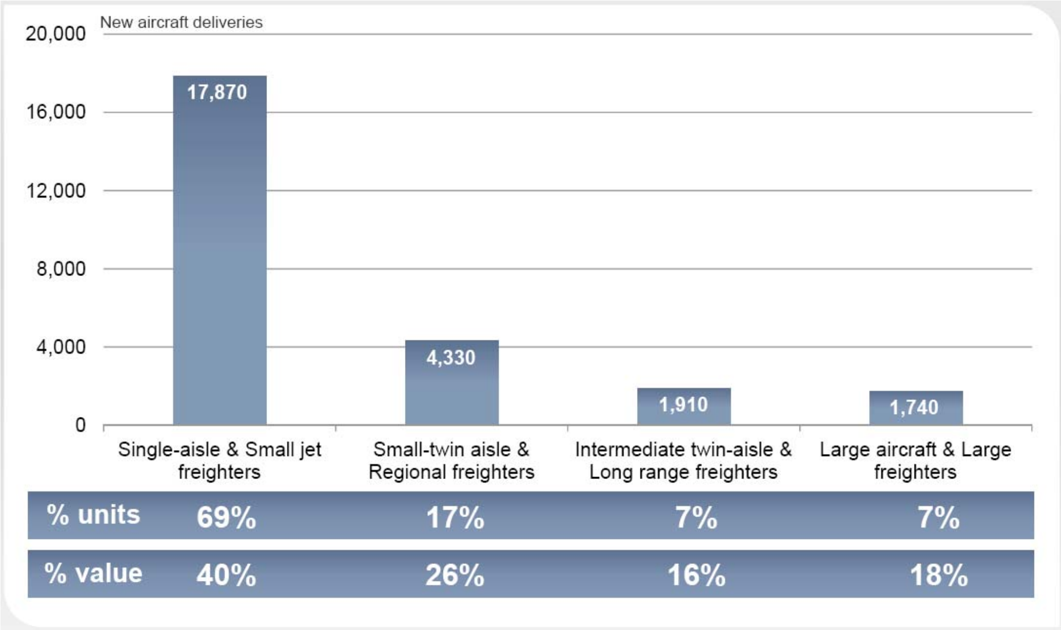

Figure A-7 20-year New Deliveries of Passenger and Freighter Aircraft [29]

Boeing Outlook

According to Boeing Global Market Forecast 2011-2030, the long-term growth rate of aviation industry will be approximately 5 percent per year shown as Figure A-8 [30].

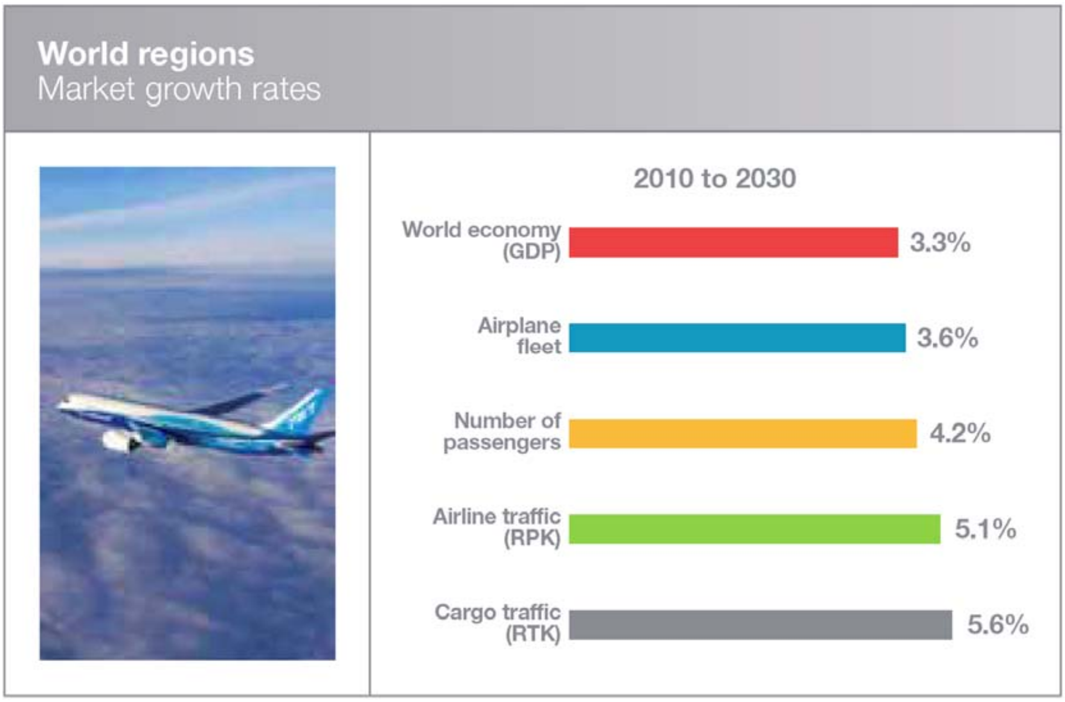

Figure A-8 Market Growth Rates [30]

In the next 20 years, 7,330 new twin-aisle aircrafts are predicted to deliver into the market (Table A-1). This represents 22 percent of total deliveries (Figure A-9), or 43 percent of total market value (Figure A-10).

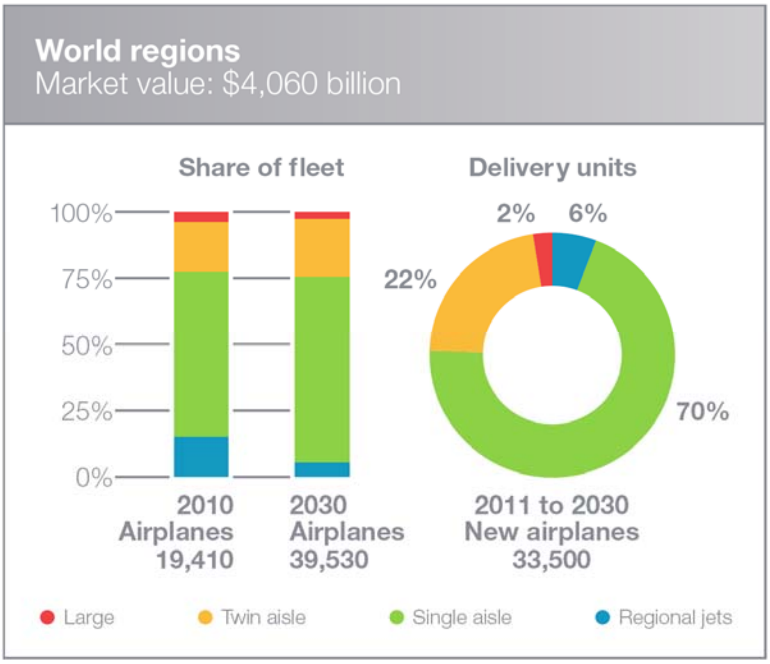

Figure A-9 Market Value in the World [30]

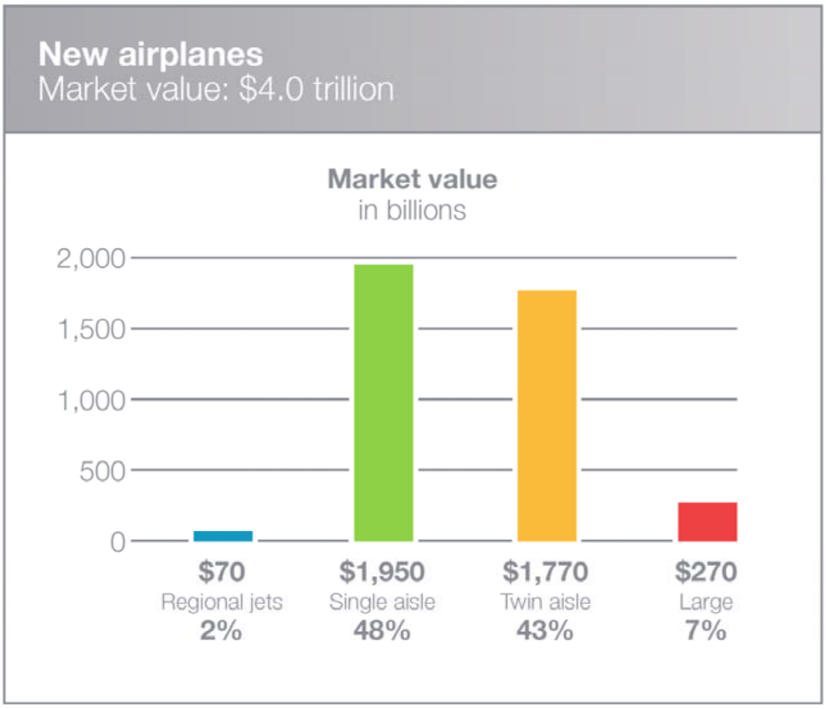

Figure A-10 Market Value in the World [30]

Table A-1 The New Delivery Aircrafts and Value Forecast [30]

Airplanes in service 2010 and 2030			Demand by size 2011 to 2030		
Size	**2010**	**2030**	**Size**	**New airplanes**	**Value ($B)**
Large	770	1,140	Large	820	270
Twin aisle	3,640	8,570	Twin aisle	7,330	1,770
Single aisle	12,100	27,750	Single aisle	23,370	1,950
Regional jets	2,900	2,070	Regional jets	1,980	70
Total	**19,410**	**39,530**	**Total**	**33,500**	**4,060**

COMAC Outlook

In order to develop China's own civil aircraft industry, in February 2008, the large aircraft project was approved by Chinese government, and Commercial Aircraft Corporation of China (COMAC) had been established to develop this project.

COMAC predicts that the growth rate of air traffic during the next 20 years (2009-2029) will increase 5.2% annually. From 2009 to 2029, 30230 new aircrafts will be delivered into the global market, it values 3,396 billion dollars. Among them, 6047 new small and medium twin-aisle aircrafts will enter into the market and the value is 1,379 billion dollars, which is about 40% of the overall market value, shown as Table 4-2 [31].

Table A-2 The New Delivery Aircrafts and Value Forecast [31]

Airplane delivery between 2009 and 2029					
		Global		**China**	
	seats	New aircraft deliveries	Value (Billion dollar)	New aircraft deliveries	Value (Billion dollar)
Turbofan regional jet	50	141	3.5	9	0.2
	70	807	29	72	2.6
	90	2,445	101	606	24.4
Single jet	120	3840	251.1	389	25.5
	160	13723	1,111.50	2,204	178.5
	200	2358	217.9	357	33.2
Dual jet	250	4592	968.8	559	118.6
	350	1455	410.9	163	45.9
	400	869	302.6	80	27.9
Total		30230	3,396.30	4,439	456.8

National Strategy of China

In order to reduce the risk, China should develop its large civil aircraft industry step by step, to divide the whole progress into 4 stages (Figure A-11). To accordant with this strategy, the flying wing aircraft should accommodate 250 passengers and have the capability to convert to 350 seats aircraft.

		Global	
	seats	New aircraft deliveries	Value (Billion dollar)
Turbofan regional jet	50	141	3.5
	70	807	29
	90	2,445	101
Single jet	120	3840	251.1
	160	13723	1,111.50
	200	2358	217.9
Dual jet	250	4592	968.8
	350	1455	410.9
	400	869	302.6

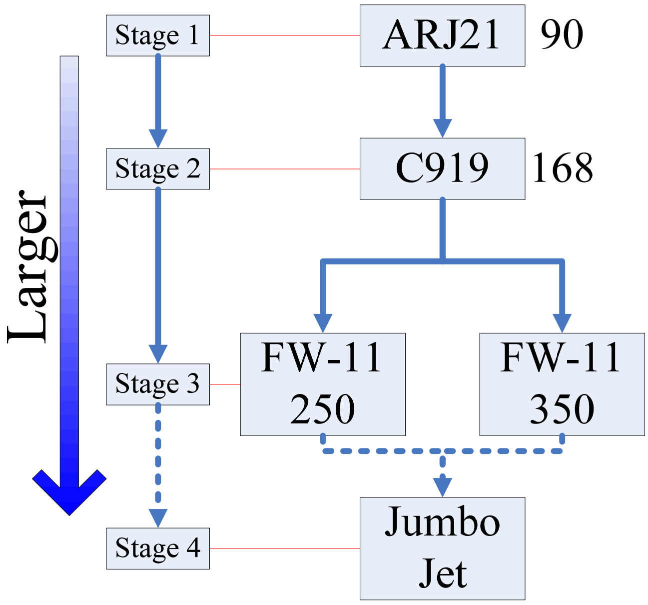

Figure A-11 Strategy of China's Civil Aviation Industry

Conclusion

From the market outlook of ICAO, Airbus, Boeing and Comac, the conclusion is clear: In the long term, world economy is expected to grow at 3.2% per annum and the global traffic will continue to increase in terms of passenger and freight air transport. Among the commercial aircraft demand for the next two decades, small and medium twin-aisle aircraft which can accommodate 250 to 350 passengers have more than 40% market share. Take China's strategy of developing large civil aircraft into consideration, the FW-11 should focus on the small and medium twin-aisle aircraft.

A.2.2 Target Market

From the market analysis above, the new FW-11 will focus on the global market, and the primary target markets should be the Asia pacific region, Europe and North American.

A.2.3 Requirements

Requirements include general requirements, seating capacity, range, speed, field performance, cost, operating and development requirements.

A.2.3.1 General Requirements

In order to focus on the global market, the FW-11 must meet the airworthiness regulations of CAAC (Civil Aviation Administration of China), FAR and EASA.

A.2.3.2 Seating Capacity

As described above, the seating capacity of FW-11 is 250 seats (single class cabin), and it should have the capability to convert to 350 seats version while considering the family issue.

A.2.3.3 Range Requirement

The principle for the FW-11 range should cover any region pair of the three regions: Asia-Pacific Region, Europe and North American. Thus 7,500 nautical miles is essential for the range requirement. Figure A-12, Figure A-13 and Figure A-14 show the coverage of 7500 nm fly from Beijing, London and New York respectively.

Figure A-12 7500 nm Range Coverage from Beijing

Figure A-13 7500 nm Range Coverage from London

Figure A-14 7500 nm Range Coverage from New York

A.2.3.4 Speed Requirement

The aircraft being developed is in the same class with the existing Boeing B767-200ER, B787-8, Airbus A330-200. The speed of B767-200 is M0.80; A330-200 cruises at M0.82; The Mach number of B787-8 is M0.85. Thus, the speed from M0.80 to M0.85 is reasonable.

A.2.3.5 Field Performance Requirement

Both A330-200 and B787-8 are taking-off and landing at 4E airports, as their wing spans are about 60 metres, larger than 52 metres. In order to make sure FW-11 can win the competition, the minimum field performance requirement for FW-11 should be taking-off and landing in the 4E airports.

A.2.3.6 Cost and Operating Requirement

The unit cost of B787, the primary competitor of FW-11, are 185 million US dollars, the FW-11 should not beyond this value. Thus, the unit cost of FW-11 should less than 185 million US dollars and the Operating Empty Weight should less than 110,000 kg, shown as Figure A-15.

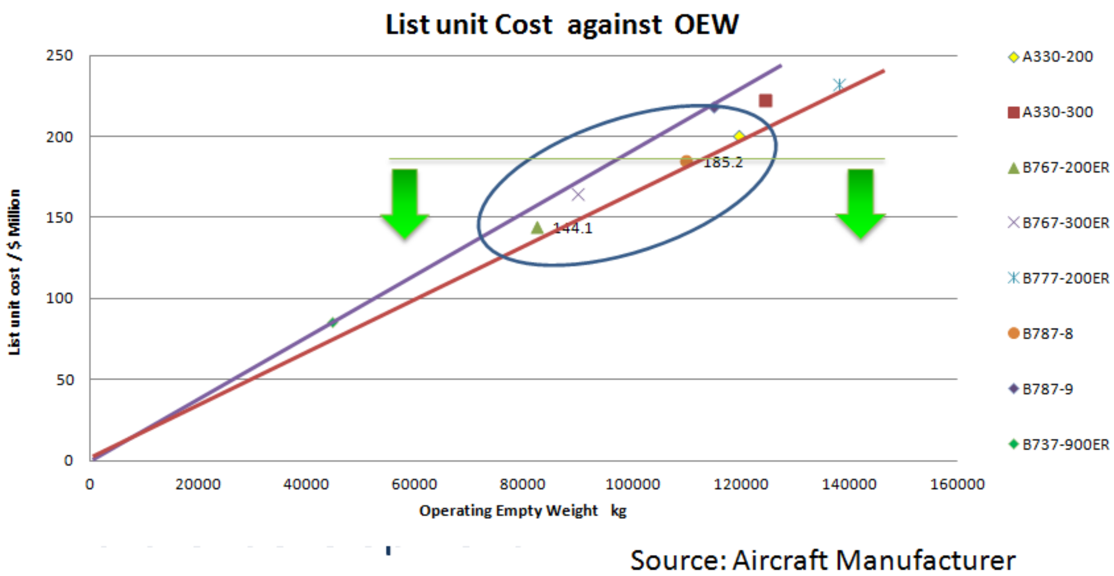

Figure A-15 List Unit Cost Statistics

The FW-11 should be designed to reduce the life cycle cost largely, thus it must improve the fuel efficiency by at least 25% of the existing in service aircraft such as A330-200, since Boeing declaim that B787 can burn 20% less fuel than the similar class aircrafts.

A.2.3.7 Noise

From the noise reduction expectation from ICAO, the FW-11 should reduce the noise about 20.5dB at least, shown as Figure A-16.

Independent Expert Panel aircraft noise reduction technology goals

Aircraft Category	Margin to Chapter 4 (EPNdB)	
	Medium Term (2018)	Long Term (2028)
Regional Jet	13.0±4.6	20.0±5.5
Small-Medium-Range Twin	21.0±4.6	23.5±5.5
Long-Range Twin	20.5±4.6	23.0±5.5
Long-Range Quad	21.0±4.6	23.5±5.5

Figure A-16 Noise Reduction Targets [28]

A.2.3.8 Further Development

As discussed above, the FW-11 should have the capability to accommodate 350 passengers whilst take family issue into consideration.

The FW-11 also should have the potential to convert to cargo aircraft, in another word, it should have freighter variant. The passenger aircraft can be convert to freighter whilst approaching the end of life to reduce the risks.

A.2.3.9 Conclusion

In conclusion, the requirements for FW-11 are shown as Table A-3.

Table A-3 Requirements for FW-11

General Requirements	CCAR, FAR, EASA-CS
Seating Capacity	250 to 350 seats (single class)
Design Range	7500nm
Cruise Speed	M0.80-0.85
Field Performance	Taking-off and Landing at 4E airport
Cost	Unit price less than $185 million
Operating Cost	25% fuel reduction compared with A330-200
Noise Reduction	20.5 dB noise reduction
Further development	Flexible operating capabilities
Entry Service Time	2020

A.3 Cruising Performance Calculation

The cruising stage is usually the flight phase which most of the fuel is burned, thus the cruising performance is extremely crucial in considering an aircraft's performance, especially for the civil aircraft which fuel cost takes about 30% of the total operating cost.

According to AVD course 0603 of SOE in CU, there are three cruise methods to calculate the cruising performance:

1. Constant angle of attack and constant Mach number – known as the cruise-climb method, as altitude must increase to allow atmospheric pressure to fall as aircraft weight reduces during flight.
2. Constant angle of attack and constant altitude – true airspeed will be reduced to compensate for the reducing aircraft weight during flight.

3. Constant altitude and constant Mach number – lift co-efficient is decreasing by reduce the angle of attack since the reducing aircraft weight.

Normally the first cruise method enables the aircraft cruise longer range compared with the other two methods. However, due to the operational restrictions, the third cruise method is the most frequently used method. Thus the third cruise method is chosen to calculate the cruising performance of FW-11.

The equation for the cruise method 3 is shown as below:

$$R_3 = \frac{1}{g}\left[\frac{V_{mdi}}{C}E_{max}\right]2u_i\left\{atan\frac{1}{{u_i}^2} - atan\frac{1}{\omega {u_i}^2}\right\} \quad \textbf{(A-1)}$$

Where V_{mdi} is the initial minimum drag speed, E_{max} is the maximum value for lift-drag ratio, u is the relative speed and ω is the fuel ratio ($\omega = W_i/W_f$). W_i is the initial aircraft weight, W_f is the final aircraft weight.

Based on the equation A-1, a spreadsheet was established to calculate the range of FW-11 and the baseline aircraft, which is designed for the comparison. According to the Advisory Circular AC120-27E, the average weight of each passenger is 115.7kg (winter weight), all the aircrafts to be compared are in the maximum density. The data is from the aircraft characteristic for airport planning documents. The Block performance and payload-range diagram can be gotten, shown as Figure A-17 and A-18.

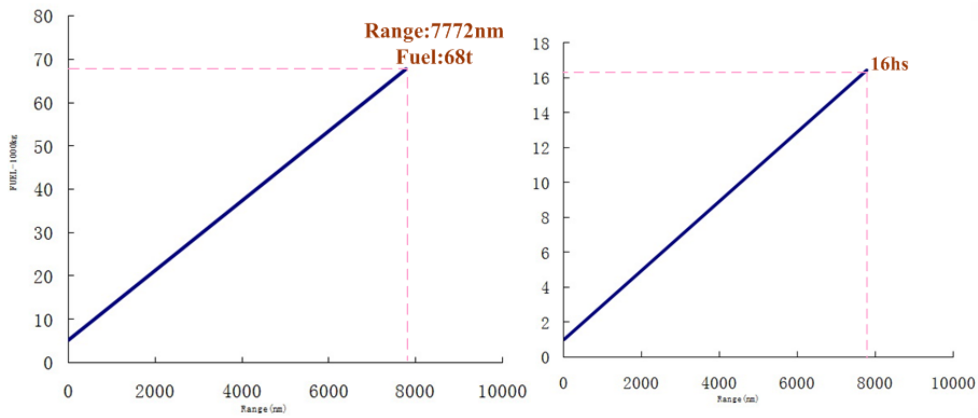

Figure A-17 Block Time and Block Fuel

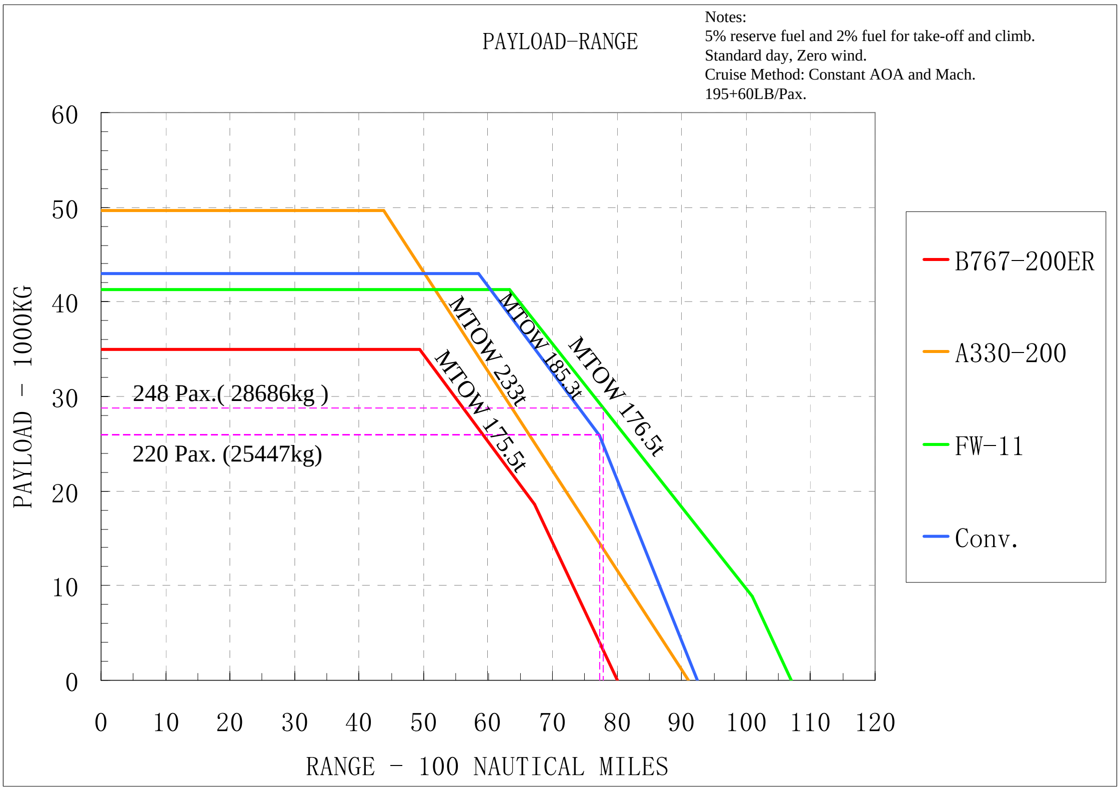

Figure A-18 Payload-Range Diagram

Table A-4 and Figure A-19 show the fuel efficiency comparison results. The FW-11 can save about 30% fuel compared with A330-200 in term of Fuel per passengers per nautical miles.

Table A-4 Cruising Performance Results

	B767-200ER	A330-200	FW-11	Baseline
seats	255	303	248	220
weight/pax(kg)	115.7	115.7	115.7	115.7
MTOW(kg)	175540	233000	176469	185278
OEW(kg)	82377	109100	75044	78537
payload(kg)	29496	35048	28686	25447
Payload&OEW(kg)	111873	144148	103730	103984
Payload Range(nm)	5600	5656	7772	7721
fuel capacity(kg)	63667	88852	72739	81294
Fuel used(kg)	60484	84409	67647	75604
Fuel/pax/nm(kg)	0.042	0.049	0.035	0.045

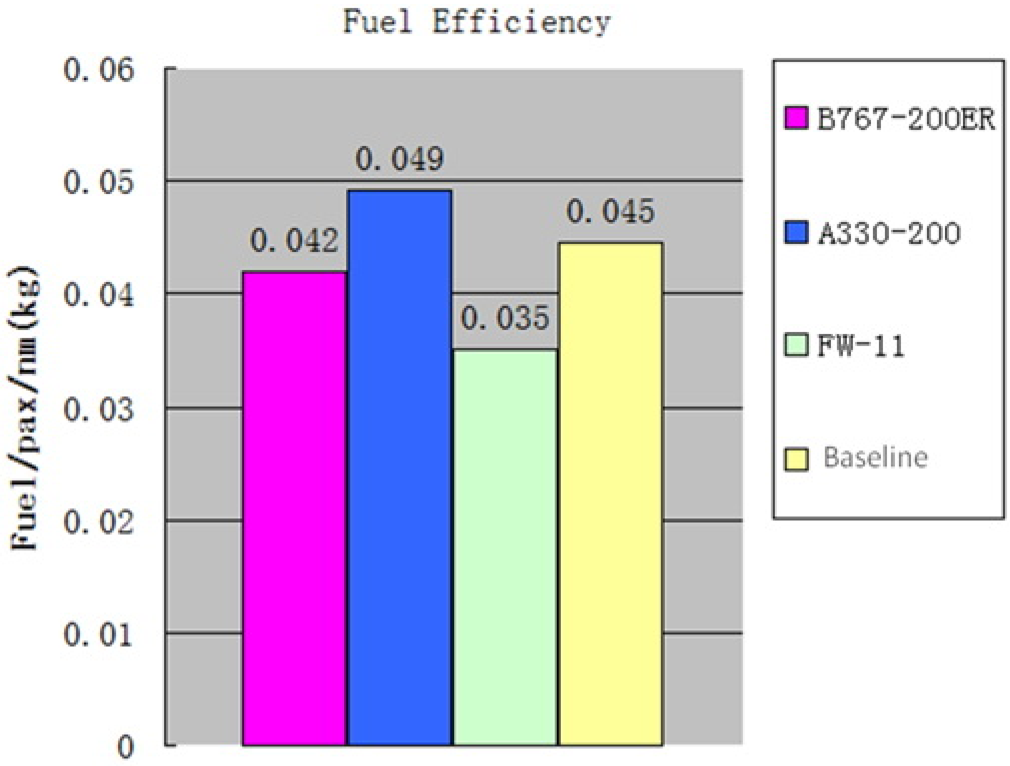

Figure A-19 Fuel Efficiency Comparison

A.4 Conclusion of GDP Work

In the Group Design Project of FW-11, the author collected data from the World Bank, ICAO, Airbus, Boeing, COMAC and other sources. Based on the data collected, analyzed the requirements of market, and then proposed the requirements for the FW-11 design inputs.

The author was also in charge of the cruising performance calculation during the whole design approach of FW-11, calculated the cruising performance for the baseline and flying wing aircraft, compared the new designed aircrafts with the civil airliners in service. As a fuel system engineer, the author gave recommendations about the fuel system, especially the criteria for the fuel tanks.

Appendix B Fuel System FHA Summary

The detail FHA results of the assumed fuel system of FW-11 are shown as the following tables.

Table B-1 Fuel System FHA Summary

Function	Failure Condition	Phase	Effect on Aircraft / Crew / Occupants	Severity
To supply fuel to each engine with pressurized fuel flow	Loss of pressurized fuel flow to both engines	Takeoff, Landing	Loss of engine thrust and power. Both engines may flame out.	Catastrophic
	Loss of pressurized fuel flow to both engines	Flight	Loss of engine thrust and power. Both engines may flame out.	Hazardous
	Loss of pressurized fuel flow to one engine	Takeoff, Flight Landing	Loss of engine thrust and power. One engine may flame out. Control trim required due to asymmetric thrust.	Major
To maintain the safety operation of the aircraft in all flight phases	Fuel tank catching on fire or even fuel tank explosion	All	Air accident	Catastrophic
To Shut off engine fuel feed	unable to shut off fuel feed flow to the nacelle(s) in the event of catching on fire	All	Loss of ability to isolate engine compartment from fuel flow.	Catastrophic

Table B-1 Fuel System FHA Summary (Cont.)

Function	Failure Condition	Phase	Effect on Aircraft / Crew / Occupants	Severity
To shut off APU fuel feed	Unable to shut off fuel feed flow to the APU in the event of catching on fire	All	Loss of ability to isolate APU compartment from fuel flow.	Catastrophic
Correct the fuel imbalance	Inability to perform cross feed function when lateral asymmetry occurred.	Flight	Loss of ability to eliminate lateral imbalance caused by fuel system. Control trim or engine thrust adjustment required due to lateral asymmetry.	Major
APU fuel feed	Loss of pressurized fuel supply to APU	ALL	Loss of auxiliary power Loss of one of the emergency powers	Major
To eject fuel to the collector tanks	Loss of motive fuel transfer	Flight	Insufficient fuel transfer to the collector tanks. Unusable fuel increased. Water accumulation.	minor
Fuel tanks vent	Fuel tanks venting blockage	Flight	Structural damage caused by large pressure difference between fuel tanks and outer atmosphere while climbing or descending	Hazardous
	Fuel tanks venting blockage	Ground	Inability to accomplish the refuel operation. May damage the fuel tank structure.	Major

Table B-1 Fuel System FHA Summary (Cont.)

Function	Failure Condition	Phase	Effect on Aircraft / Crew / Occupants	Severity
To perform the automatic pressure refuelling	Loss of automatic pressure refuelling capability	Ground	Ground crew can use manual mode. Possible dispatch delay.	Minor
	Inability to sends signals to the refuel valve shutoff the refuelling flow at the desired fuel quantity	Ground	Ground crew needs to check the validation of fuel indication subsystem. No damage to the fuel system.	Minor
To indicate the cross feed valve position	Fuel cross feed open message inoperative	Flight	Lateral imbalance would occur if one or more AC boost pumps are failed.	Minor
To maintain the fuel temperature in an appropriate range	The fuel temperature is lower than the freezing point or exceeds the designated point.	All	The fuel feed lines to the engines may be blocked. High fuel temperature may cause fuel tank explosion.	Catastrophic

Table B-1 Fuel System FHA Summary (Cont.)

Function	Failure Condition	Phase	Effect on Aircraft / Crew / Occupants	Severity
Indicate accurate fuel quantity data related to the fuel tanks	Loss of fuel quantity data from left or right or centre tanks	Flight	Crew shall use fuel consumed data to derive fuel remaining for failed tank displays.	Minor
	Loss of fuel quantity data from all the tanks	Flight	Crews can only derive the remaining fuel for failed tank displays through the fuel consumed data. Crews were not aware of the malfunction of fuel tank leakage.	Major
	Loss of fuel quantity data from all the tanks and loss of fuel low level warning	Flight	Crews were not aware of the situation of insufficient remaining fuel.	Hazardous
	Erroneous left or right or centre fuel tanks quantity data provided to the cockpit displays	Flight	Crews may unable to recognize the invalid data display	Minor
	Erroneous all fuel tanks quantity data provided to the cockpit displays	Flight	Crews are unable to recognize the invalid data display	Major

Table B-1 Fuel System FHA Summary (Cont.)

Function	Failure Condition	Phase	Effect on Aircraft / Crew / Occupants	Severity
To indicate accurate fuel low level of collector tanks	Loss of fuel low level data from left or right collector tanks	Flight	Extra observation of fuel quantity data of each tank conducted by the crews is needed.	Minor
	Loss of fuel low level data from left and right collector tanks	Flight	Extra observation of fuel quantity data of each tank conducted by the crews is needed.	Major
	Erroneous fuel low level indication from one of the collector tanks	Flight	Crews must determine the validation of fuel quantity display.	Minor
	Erroneous fuel low level indication from both collector tanks	Flight	Crews must determine the validation of fuel quantity display.	Major

Table B-1 Fuel System FHA Summary (Cont.)

Function	Failure Condition	Phase	Effect on Aircraft / Crew / Occupants	Severity
To indicate the fuel imbalance	Imbalance signal appear when no fuel tank imbalance condition exists.	Flight	Crew needs to check the fuel quantity data displayed in the display.	Minor
	No imbalance signal display when fuel tank imbalance condition exists.	Flight	Control trim needed	Minor
	No imbalance signal display after single engine shut down during flight.	Flight	Control trim needed	Minor

Appendix C Fuel System FMEA Summary

The detail FMEA results of the assumed fuel system of FW-11 are shown as the following tables.

Table C-1 Fuel System FMEA Summary

Component: AC boost pump Component function: provides pressurized fuel flow to the engines, APU and ejector pumps.				
Failure mode	Effect on fuel system	Effect on the aircraft	Hazard class	Flight Phase
Loss of fuel flow	Loss of associated pump fuel flow	Reduced fuel feed flow.	Major	Ground & flight
Low pressure fuel feed	Reduced associated pump fuel flow	Reduced fuel feed flow.	Minor	Ground & flight
Failed to shut down the pump when overheated	Heat the associated fuel tank	Possible fuel tank explosion.	Hazardous	Ground & flight
Check valve failed to close	When the associated pump is not in use, fuel is delivered back the fuel tank.	Reduced fuel feed flow. Possible lateral imbalance when cross feed was in operation.	Major	Ground & flight
Internal fuel leakage	Reduced associated pump fuel flow	Reduced fuel feed flow.	Minor	Ground & flight

Table C-1 Fuel System FMEA Summary (Cont.)

Component: DC APU pump Component function: provides pressurized fuel to APU				
Failure mode	Effect on fuel system	Effect on the aircraft	Hazard class	Flight Phase
Loss of fuel flow	Loss of associated pump fuel flow	Reduced fuel feed flow.	Major	Ground & flight
Low pressure fuel feed	Reduced associated pump fuel flow	Reduced fuel feed flow.	Minor	Ground & flight
Fails to shut down the pump when overheated	Heat the associated fuel tank	Possible fuel tank explosion.	Hazardous	Ground & flight
Check valve fails to close	When the associated pump is not in use, fuel is delivered back the left collector tank.	Reduced fuel feed flow. Possible lateral imbalance when cross feed was in operation.	Major	Ground & flight
Internal fuel leakage	Reduced associated pump fuel flow	Reduced fuel feed flow.	Minor	Ground & flight

Table C-1 Fuel System FMEA Summary (Cont.)

Component: engine feed shutoff valve

Component function: isolate the fuel flow from engine(s) in case of fire or shut off fuel flow when feed line ruptured.

Failure mode	Effect on fuel system	Effect on the aircraft	Hazard class	Flight Phase
Fails to open	Loss of fuel flow in associated engine fuel feed line	Unable to start associated engine	Major	Ground & flight
Fails to close	Inability to shut off fuel flow in associated fuel feed line	Loss of fuel feed line isolation from engine fire or fuel line rupture	Hazardous	Ground & flight
Internal leak	Inability to shut off fuel flow in associated fuel feed line	Unable to isolate fuel flow from engine fire or fuel line rupture.	Major	Ground & flight
External leak	Fuel feed line leaks into the outer tube	Ground crew needs to drain the associate double wall tube	Minor	Ground & flight
Loss of valve position	Erroneous shutoff valve indication	Caution message generated	Minor	Ground & flight

Table C-1 Fuel System FMEA Summary (Cont.)

Component: APU feed shutoff valve Component function: isolate the fuel flow from APU in case of fire or shut off fuel flow when feed line ruptured.				
Failure mode	Effect on fuel system	Effect on the aircraft	Hazard class	Flight Phase
Fails to open	Loss of fuel flow in APU fuel feed line	Unable to start APU	Major	Ground & flight
Fails to close	Inability to shut off fuel flow in APU fuel feed line	Loss of fuel feed line isolation from APU fire or fuel line rupture	Hazardous	Ground & flight
Internal leak	Inability to shut off fuel flow in APU fuel feed line	Unable to isolate fuel flow from APU fire or fuel line rupture completely.	Major	Ground & flight
External leak	Fuel feed line leaks into the outer tube	Ground crew needs to drain the APU double wall tube	Minor	Ground & flight
Loss of valve position	Erroneous shutoff valve indication	Caution message generated	Minor	Ground & flight

Table C-1 Fuel System FMEA Summary (Cont.)

Component: cross feed shutoff valve Component function: isolates the left and right fuel feed lines and provides cross fuel feed when needed.				
Failure mode	Effect on fuel system	Effect on the aircraft	Hazard class	Flight Phase
Fails to open	Loss of fuel cross feed function	Inability to correct lateral imbalance in flight. Subsequent engine failure will aggravate the lateral imbalance. Unable to transfer fuel in the right tanks to the left tanks in defuel operation.	Major	Ground & flight
Fails to close	Inability to isolate left and right fuel feed lines	Loss of isolation of left and right fuel feed lines	Major	Flight
Internal leak	Inability to isolate left and right fuel feed lines completely	Partly loss of isolation of left and right fuel feed lines	Major	Flight

Table C-1 Fuel System FMEA Summary (Cont.)

Component: cross feed shutoff valve

Component function: isolates the left and right fuel feed lines and provides cross fuel feed when needed.

Failure mode	Effect on fuel system	Effect on the aircraft	Hazard class	Flight Phase
External leak	Fuel feed line leaks into the Centre Tank	Reduced fuel feed flow. Increased unusable fuel.	Minor	Ground & flight
Loss of valve position	Erroneous cross feed shutoff valve indication	Caution message generated	Minor	Ground & flight

Table C-1 Fuel System FMEA Summary (Cont.)

Component: Suction feed inlet screen Component function: filter the fuel in the suction feed operation				
Failure mode	Effect on fuel system	Effect on the aircraft	Hazard class	Flight Phase
Loss of filtration function	Unable to filter the foreign matter or contamination from the fuel	Possible jams the fuel filter in the fuel feed line	Minor	Ground & flight
Component: Suction feed check valve Component function: prevents fuel flow from boost pump back to fuel tank through the suction feed inlet.				
Failure mode	Effect on fuel system	Effect on the aircraft	Hazard class	Flight Phase
Fails to open	Unable to perform the suction fuel feed when needed	Loss of engine fuel feed redundancy	Minor	Ground & flight
Fails to close	Loss of fuel feed flow and motive flow to the ejector pumps in flight	Reduced engine fuel feed flow	Major	Ground & flight

Table C-1 Fuel System FMEA Summary (Cont.)

Component: scavenge ejector pump

Component function: transfers fuel to the collector tanks from other designated fuel tanks

Failure mode	Effect on fuel system	Effect on the aircraft	Hazard class	Flight Phase
Loss of fuel flow	Unable to transfer fuel to the associated collector tank; Inability to scavenge the water contamination from fuel	Reduced fuel transfer flow to the collector tank. Increased unusable fuel. Possible water accumulation in the associated fuel tank.	Minor	Ground & flight
Reduced fuel flow	Insufficient fuel transfer ability to the associated collector tank	Reduced fuel transfer flow to the collector tank.	Minor	Ground & flight
Check valve in the pump fails to open	Unable to transfer fuel to the associated collector tank; Loss of motive fuel flow from collector tank.	Reduced fuel transfer flow to the collector tank. Fuel in the collector tank backflow into the associated tank.	Major	Ground & flight

Table C-1 Fuel System FMEA Summary (Cont.)

Component: engine feed check valve Component function: prevents fuel pressure from AC boost pumps in the other collector tanks, from also having to feed the scavenge ejector pumps in the wrong fuel tanks				
Failure mode	Effect on fuel system	Effect on the aircraft	Hazard class	Flight Phase
Fails to open	Loss of pressurized fuel flow from the affected fuel tank.	Possible reduced engine fuel feed capability. Possible cross feed needed. Fuel in the affected tank is unusable.	Major	Ground & flight
Fails to close	Possible feed fuel flow to scavenge ejector pumps in the wrong fuel tanks when the boost pumps in the associated fuel feed line shutoff.	Possible reduced engine fuel feed capability. Possible increased unusable fuel.	Major	Ground & flight

Table C-1 Fuel System FMEA Summary (Cont.)

Component: AC boost pump pressure sensor Component function: senses fuel pressure in the AC boost pump outlet				
Failure mode	Effect on fuel system	Effect on the aircraft	Hazard class	Flight Phase
AC boost pump pressure sensor always indicates low fuel pressure	Erroneous indications of AC boost pump failure when AC pump is in normal condition.	Inaccurate caution message generated	Minor	Ground & flight
AC boost pump pressure sensor never indicates low fuel pressure	Inability to indicate low pressure in the AC boost pump outlet.	Pilots are not aware of the AC pump status.	Major	Ground & flight
Seal failure	External or internal fuel leakage.	External fuel spillage. Possible AC pump low pressure indication	Minor	Ground & flight

Table C-1 Fuel System FMEA Summary (Cont.)

Component: DC boost pump pressure sensor Component function: senses fuel pressure in the DC APU pump outlet				
Failure mode	Effect on fuel system	Effect on the aircraft	Hazard class	Flight Phase
DC APU pump pressure sensor always indicates low fuel pressure	Erroneous indications of DC APU pump failure when DC pump is in normal condition.	Inaccurate caution message generated	Minor	Ground & flight
DC APU pump pressure sensor never indicates low fuel pressure	Inability to indicate low pressure in the DC APU pump outlet.	Pilots are not aware of the DC pump status.	Minor	Ground & flight
Seal failure	External or internal fuel leakage.	External fuel spillage. Possible DC pump low pressure indication	Minor	Ground & flight

Table C-1 Fuel System FMEA Summary (Cont.)

Component: shroud drain valve Component function: drains the fuel leakage in the outer tube of double-wall fuel feed tubes and indicates the status of inner tubes.				
Failure mode	Effect on fuel system	Effect on the aircraft	Hazard class	Flight Phase
Fails to open	Unable to drain the trapped fuel from the outer tube of associated fuel feed lines.	None	Minor	Ground
Fails to close	Overboard fuel leakage from the fuel feed lines when the inner tube leaks.	None	Minor	Ground & flight

Table C-1 Fuel System FMEA Summary (Cont.)

Component: refuel/defuel adapter Component function: interface to refuel truck or ground refuelling station				
Failure mode	Effect on fuel system	Effect on the aircraft	Hazard class	Flight Phase
Single adapter damage	Unable to remove refuel adapter cap or connect fuel nozzle	Reduced pressure refuelling capability	Minor	Ground
Both adapters damage	Unable to remove refuel adapter cap or connect fuel nozzle	Loss of pressure refuelling capability. Dispatch delay.	Major	Ground
Seals failure	Fuel leaking	External fuel spillage. Possible external fuel spillage in the jettison operation.	Minor	Ground & flight

Table C-1 Fuel System FMEA Summary (Cont.)

Component: refuel valve Component function: enables or disables refuelling flow to each fuel tank				
Failure mode	Effect on fuel system	Effect on the aircraft	Hazard class	Flight Phase
Fails to open	Unable to feed fuel from refuel/defuel manifold to the associated fuel tanks.	Unable to refuel associated fuel tanks. Dispatch delay.	Minor	Ground
Fails to close	Unable to shut off refuelling flow to the associated fuel tanks. Possible fuel tanks overfill or fuel spillage overboard.	Possible fuel spillage.	Major	Ground

Table C-1 Fuel System FMEA Summary (Cont.)

Component: float valve Component function: shut off the refuel valve when fuel level reached the designated level during refuel operation				
Failure mode	Effect on fuel system	Effect on the aircraft	Hazard class	Flight Phase
Fails to open	Inability to open the associated refuel valve	Unable to refuel associated fuel tanks. Dispatch delay.	Minor	Ground
Fails to close	Unable to close associated refuel valve and stop refuelling flow to the associated tanks. Possible fuel tanks overfill or fuel spillage overboard.	Possible fuel spillage.	Major	Ground

Table C-1 Fuel System FMEA Summary (Cont.)

Component: manifold isolation valve Component function: provides isolation between engine feed and refuel manifolds				
Failure mode	Effect on fuel system	Effect on the aircraft	Hazard class	Flight Phase
Fails to open	Loss of defuel function	Unable to defuel the aircraft	Minor	Ground
Fails to close	Loss of isolation between engine feed and refuel manifolds.	None	Minor	Ground & flight
External leak	Left engine fuel feed line leaks fuel into centre fuel tank	Reduced left engine fuel feed flow. Increased unusable fuel.	Major	Flight
Internal leak	Unable to stop fuel flow while defueling when commanded.	Unable to stop fuel flow completely while defueling when commanded. Loss of isolation.	Minor	Ground & flight
Loss of valve position	Erroneous indication of defuel shutoff valve failure	Advisory message generated	Minor	Ground & flight

Table C-1 Fuel System FMEA Summary (Cont.)

Component: refuel pressure switch Component function: senses pressure of refuel manifold				
Failure mode	Effect on fuel system	Effect on the aircraft	Hazard class	Flight Phase
Always indicates low pressure	Erroneous low pressure indication of refuel manifold	Loss of the overpressure protection of refuel manifold	Major	Ground
Never indicates low pressure	Erroneous high pressure indication of refuel manifold	Erroneous indication that close the refuel valve	Minor	Ground
Seal failure	External fuel leakage. Possible low pressure indication of refuel manifold	External fuel spillage. Possible loss of the overpressure protection of refuel manifold	Major	Ground

Table C-1 Fuel System FMEA Summary (Cont.)

Component: integrated refuel panel Component function: provides interface to ground crews for refuel and defuel operation				
Failure mode	Effect on fuel system	Effect on the aircraft	Hazard class	Flight Phase
Loss of refuel/defuel power on/off selection	Unable to control application of power	Loss of refuel function. Possible dispatch delay.	Minor	Ground
Loss of manual control of refuel valve	Unable refuel the fuel tanks manually	Loss of manual refuelling function	Minor	Ground
Loss of automatic control of refuel valve	Unable to refuel the fuel tanks automatically	Loss of automatic refuel function	Minor	Ground
Loss of control of manifold isolation valve	Unable to defuel the fuel tanks	Loss of defuel function	Minor	Ground

Table C-1 Fuel System FMEA Summary (Cont.)

Component: flame arrestor Component function: provides external fire blockage for surge tanks.				
Failure mode	Effect on fuel system	Effect on the aircraft	Hazard class	Flight Phase
Clogged element	Loss of vent function while refuelling.	Loss of refuel function	Major	Ground
	Loss of backup vent path.	Loss of venting redundancy	Major	Flight

Component: water drain valve Component function: drains the water from the sump of fuel tanks				
Failure mode	Effect on fuel system	Effect on the aircraft	Hazard class	Flight Phase
Fails to open	Unable to remove water from associated fuel tanks	None	Minor	Ground
Fails to close	External fuel leakage	External fuel spillage	Minor	Ground

Table C-1 Fuel System FMEA Summary (Cont.)

Component: flapper check valve in the structure ribs Component function: allows fuel flow from outboard tanks to inboard tanks and prevents fuel flow to reverse direction.				
Failure mode	Effect on fuel system	Effect on the aircraft	Hazard class	Flight Phase
Fails to open	Unable to pass fuel inboard	Only significant if multiple valves and ejector pumps failure.	Minor	Ground & flight
Fails to close	Unable to prevent fuel backflow	Only significant if multiple valve failure	Minor	Ground & flight
Component: flapper check valve in the spanwise beams Component function: allows fuel flow from backward tanks to forward tanks and prevents fuel flow to reverse direction.				
Failure mode	Effect on fuel system	Effect on the aircraft	Hazard class	Flight Phase
Fails to open	Unable to pass fuel forward	Only significant if multiple valves and ejector pumps failure.	Minor	Ground & flight
Fails to close	Unable to prevent fuel backflow	Reduced fuel transfer capability.	Major	Ground & flight

Table C-1 Fuel System FMEA Summary (Cont.)

Component: fuel management computer

Component function: processes signals from the sensors to perform monitoring and controlling of the fuel system

Failure mode	Effect on fuel system	Effect on the aircraft	Hazard class	Flight Phase
Loss of fuel quantity processor operation	Loss of fuel quantity data for associated tanks, automatic refuel, low fuel level warning functions.	Loss of fuel quantity data, automatic refuel, low fuel level warning functions.	Hazardous	Ground & flight
Loss of operation of Bus communication	Loss of fuel quantity data for associated tanks, automatic refuel, low fuel level warning, and critical fuel temperature warning functions.	Loss of monitoring function and partly loss of control ability.	Hazardous	Ground & flight
Loss of signal from fuel quantity probe	Loss of fuel quantity data of associated tanks.	Loss of fuel quantity data of associated tanks.	Hazardous	Ground & flight
Loss of signal from fuel densitometer	Inaccurate fuel quantity data of associated tanks.	Inaccurate fuel quantity data of associated tanks.	Major	Ground & flight

Table C-1 Fuel System FMEA Summary (Cont.)

Component: fuel management computer Component function: processes signals from the sensors to perform monitoring and controlling of the fuel system				
Failure mode	Effect on fuel system	Effect on the aircraft	Hazard class	Flight Phase
Loss of signal from low fuel level sensor	Loss of low fuel warning function	Loss of low fuel warning function	Hazardous	Flight
Loss of signal from fuel temperature sensor	Loss of critical fuel temperature warning function	Loss of critical fuel temperature warning function	Hazardous	Flight
Component: fuel quantity probe Component function: measures fuel level				
Failure mode	Effect on fuel system	Effect on the aircraft	Hazard class	Flight Phase
Loss of valid output	Erroneous indication of fuel quantity	Loss of fuel quantity data of associated tanks	Major	Ground & flight
Inaccurate output	Erroneous indication of fuel quantity	Inaccurate fuel quantity data of associated tanks	Major	Ground & flight

Table C-1 Fuel System FMEA Summary (Cont.)

Component: fuel densitometer Component function: provides fuel density data to FMC				
Failure mode	Effect on fuel system	Effect on the aircraft	Hazard class	Flight Phase
Loss of valid output	Inaccurate fuel quantity data of associated fuel tanks	Inaccurate fuel quantity data of associated fuel tanks	Minor	Ground & flight
Inaccurate output	Inaccurate fuel quantity data of associated fuel tanks	Reduced fuel quantity data accuracy	Minor	Ground & flight
Component: fuel low level sensor Component function: indicates the low fuel level				
Failure mode	Effect on fuel system	Effect on the aircraft	Hazard class	Flight Phase
No signals output	Loss of valid output from associated collector tanks	Loss of low fuel level warning.	Major	Flight
Always low level	Erroneous warning message generated	Erroneous warning message generated	Major	Flight

Table C-1 Fuel System FMEA Summary (Cont.)

Component: fuel temperature sensor Component function: detects fuel temperature in each tank				
Failure mode	Effect on fuel system	Effect on the aircraft	Hazard class	Flight Phase
Loss of valid output	Loss of fuel temperature data of associated fuel tanks	Loss of fuel temperature monitoring function	Major	Ground & flight
Inaccurate output	Inaccurate fuel temperature data of associated fuel tanks	Possible inaccurate low fuel temperature warning generated	Major	Ground & flight
Component: fuel tank pressure sensor Component function: senses surge tank pressure				
Failure mode	Effect on fuel system	Effect on the aircraft	Hazard class	Flight Phase
Always indicates low/high pressure	Erroneous indication of surge tank pressure	Wrong warning message generated	Major	Ground & flight
Never indicates low/high pressure	Unable to indicate critical pressure condition in surge tank	Loss of warning function	Hazardous	Ground & flight

Table C-1 Fuel System FMEA Summary (Cont.)

Component: OBIGGS Component function: generates nitrogen enriched air to inert fuel tanks				
Failure mode	Effect on fuel system	Effect on the aircraft	Hazard class	Flight Phase
Unable to generates NEA	Loss of inerting function in the fuel tank	Loss of fuel tank explosion suppression function	Major	Ground & flight
Reduced NEA generation	Loss of inerting function in the fuel tank	Reduced fuel tank explosion suppression capability	Minor	Ground & flight
Component: heat exchanger Component function: cool down the inerting subsystem and hydraulic system				
Failure mode	Effect on fuel system	Effect on the aircraft	Hazard class	Flight Phase
Heat exchanger overheat	Possible ignition source in the fuel tank	Possible fuel tank explosion	Hazardous	Ground & flight
Working fluid leakage	Fuel system contamination	Maintenance action required	Major	Ground & flight